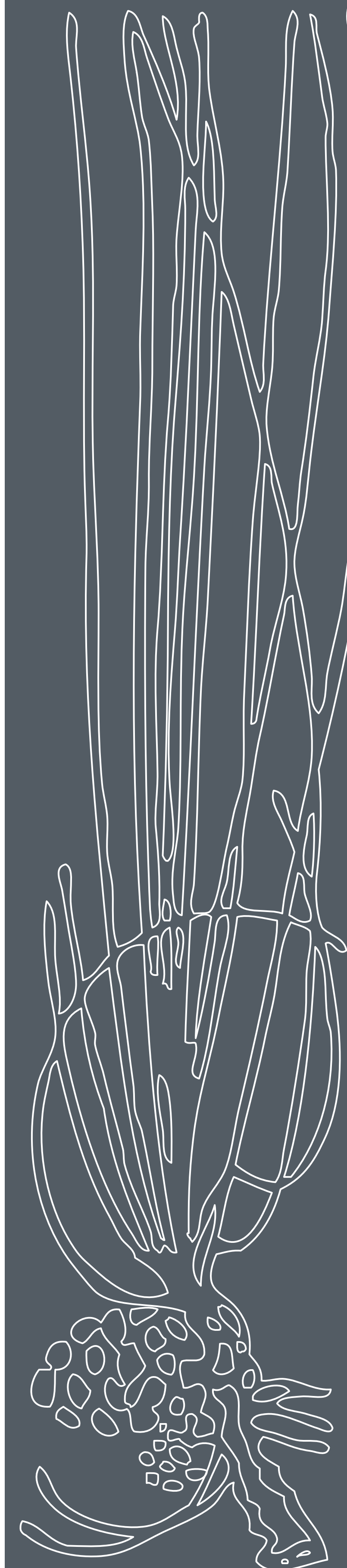
Henriikka Salminen is a physical geographer whose research focuses on the dynamics of fine-scale geodiversity in northern environments. In her doctoral thesis, she investigates how fine-scale geodiversity can be identified through geofeatures and how it varies across landscapes, including the development of a field method for its measurement and quantification. Her research further explores the relationships between fine-scale geodiversity and biodiversity – particularly the species richness of vascular plants, bryophytes, and lichens in Boreal–Arctic heath ecosystems. She also examines how ski tourism-related land use influences geodiversity in Finnish Lapland. Through her work, Salminen seeks to highlight the practical value of fine-scale geodiversity information for nature conservation and sustainable land management.

University of Oulu Graduate School

Publication of The Geographical Society of Northern Finland & Geography Research Unit at University of Oulu

ISBN 978-952-62-4876-9 (print)
ISBN 978-952-62-4877-6 (online)

Painosalama 2026



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nordia geographical publications

55:2

Fine-scale geodiversity in northern environments – connections with biodiversity patterns and land use

Henriikka Salminen

nordia
geographical
publications

volume 55 issue 2

Fine-scale geodiversity in northern environments – connections with biodiversity patterns and land use

Henriikka Salminen

Academic dissertation to be presented with the permission of the Doctoral Training Committee for Technology and Natural Sciences of the University of Oulu Graduate School (UniOGS) for public discussion in the lecture hall L2 on the17th of April 2026 at 12.

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Nordia Geographical Publications is a publication of The Geographical Society of Northern Finland and Geography Research Unit at the University of Oulu. Address: PO Box 3000 FIN-90014 University of Oulu. Web: www.nordia.journal.fi. Editor-in-chief: Helena Tukiainen, helena.tukiainen@oulu.fi. Associate editors: Henriikka Salminen and Maija Toivanen. Layout editor: Maija Toivanen. Cover and layout design: Maija Toivanen.

ISBN 978-952-62-4876-9 (print)
ISBN 978-952-62-4877-6 (online)
ISSN 1238-2086 (print)
ISSN 2736-9722 (online)

Printed at Painosalama, Turku, 2026

Contents

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Abstract

Geodiversity is gaining recognition in research and is an important addition to holistic ways of understanding and studying nature. However, there is a lack of fine-scale methods to observe and quantify fine-scale geodiversity. This thesis aims to improve our understanding of fine-scale geodiversity in northern environments. First, I explore how fine-scale geodiversity can be observed through geofeatures that are elements of geodiversity. Further, I examine how fine-scale geodiversity varies, and how it can be quantified. Second, I examine how fine-scale geodiversity is connected to biodiversity, explicitly to the species richness of vascular plants, bryophytes, and lichens, in Boreal-Arctic heath ecosystems. Third, I study the impact of ski tourism–related land use on fine-scale geodiversity in Finnish Lapland. Finally, I aim to identify what practitioners can get from information on fine-scale geodiversity and how it can be used in nature conservation and land management. The thesis includes three articles that apply ecological methods to geodiversity research.

I present a new field method for collecting fine-scale geodiversity data from Boreal-Arctic environments. I introduce this method, which produces a quantitative measure of georichness, i.e. the number of distinct geofeatures (geological, geomorphological, and hydrological features), but also qualitative information about the identities of geofeatures in a study plot (5, 10, and 25 m radii). Fine-scale geodiversity provides unique knowledge of the abiotic environment, geofeatures, and their interplay with biodiversity, and it can be assessed in both undisturbed and human-impacted locations. This thesis reveals that greater georichness indicates greater species richness of vascular plants, bryophytes, and lichens in continuous mountain heaths and tundra. However, this relationship is context-dependent, with other factors playing a larger role in some areas. I also present results from Finnish Lapland ski resorts that revealed geodiversity tends to be lower in areas that are heavily impacted by land use. In addition, observed geofeatures differed between areas of low, medium, and high land use intensity, suggesting geodiversity's vulnerability to human disturbance. To conclude, the fine-scale geodiversity method can be used to gather comprehensive information about geodiversity and it can be implemented in nature monitoring and evaluations to support land use planning and conservation.

Keywords: geodiversity, biodiversity, georichness, species richness, geofeature, qualitative–quantitative assessment, nature conservation, land management, Conserving Nature's Stage

Tiivistelmä (abstract in Finnish)

Geodiversiteetti on kasvattanut tunnettuuttaan tutkimuksessa ja on tärkeä lisä kokonaisvaltaiseen tapaan ymmärtää ja tutkia luontoa. Paikallisella tasolla geodiversiteettitutkimusta on tehty kuitenkin vähän. Tämän väitöskirjan tavoitteena on parantaa ymmärrystämme paikallisen tason geodiversiteetistä pohjoisissa ympäristöissä. Ensiksi tutkin, miten paikallisen tason geodiversiteettiä voidaan havaita geokohteiden eli geodiversiteetin elementtien avulla uutta kenttätyömenetelmää käyttäen. Lisäksi tarkastelen, miten paikallisen tason geodiversiteetti vaihtelee ja miten sitä voidaan tarkastella määrällisesti. Toiseksi tarkastelen, miten paikallisen tason geodiversiteetti liittyy elonkirjoon eli biodiversiteettiin, nimenomaisesti putkilokasvien, sammalten ja jäkälien lajirunsauteen boreaalisarktisten tunturikankaiden ekosysteemeissä. Kolmanneksi tutkin hiihtokeskusmatkailuun liittyvän maankäytön vaikutusta paikallisen tason geodiversiteettiin Suomen Lapissa. Lopuksi pyrin tuomaan näkökulmia siihen, mitä käytännön toimijat saavat tiedosta paikallisen tason geodiversiteetistä ja miten sitä voidaan hyödyntää luonnonsuojelussa ja maankäytössä. Tämä väitöskirja sisältää kolme artikkelia, jotka soveltavat ekologisia menetelmiä geodiversiteettitutkimuksessa.

Esittelen uuden kenttämenetelmän paikallisen tason geodiversiteettitiedon keräämiseen arktisalpiinisista ympäristöistä. Menetelmässä havainnoidaan paikallisen tason geodiversiteettiä määrällisesti ja tuotetaan arvio georunsaudesta eli erillisten geokohteiden (geologisten, geomorfologisten ja hydrologisten elementtien) lukumäärästä, mutta myös laadullista tietoa geodiversiteetin elementeistä tutkimusaloilla (5 m, 10 m ja 25 m säteiltä). Paikallisen tason geodiversiteetti tarjoaa ainutlaatuista tietoa abioottisesta luonnosta, ja sen vuorovaikutuksesta elonkirjon kanssa, jota voidaan arvioida sekä luonnollisista että ihmisvaikutteisista paikoista. Tulokset osoittivat, että suurempi paikallisen tason geodiversiteetti on yhteydessä suurempaan putkilokasvien, sammalten ja jäkälän lajirunsauteen laajoilla tunturikankailla. Tämä suhde on kuitenkin kontekstista riippuvainen, ja muilla lajirunsautta määrittävillä tekijöillä, kuten maaperän kalsiumpitoisuudella on suurempi rooli muilla tutkituilla alueilla. Suomen Lapin hiihtokeskuksissa tehdyn tutkimuksen tulokset osoittivat, että paikallisen tason geodiversiteetti on yleensä vähäisempää alueilla, joilla maankäyttö on voimakasta. Lisäksi havaitut geokohteet vaihtelivat luonnonmukaisten alojen, vähäisen maankäytön ja korkean maankäyttöintensiteetin alueiden välillä, mikä viittaa geodiversiteetin olevan haavoittuvainen ihmisen aiheuttamille häiriöille. Yhteenvetona voidaan todeta, että väitöskirjassa käytetyllä paikallisen tason maastomenetelmällä voidaan kerätä kattavasti tietoa geodiversiteetistä, ja sitä voidaan edelleen soveltaa. luonnon seurannassa ja arvioinneissa maankäytön suunnittelun ja suojelun tukemiseksi.

Avainsanat: geodiversiteetti, biodiversiteetti, georunsaus, lajirunsaus, geokohde, laadullis–määrällinen tutkimus, luonnonsuojelu, maankäyttö, CNS-luonnonsuojelustrategia

List of original publications

Article I	Hjort J, Tukiainen H, Salminen H, Kemppinen J, Kiilunen P, Snåre H, Alahuhta J & Maliniemi T (2022) A methodological guide to observe local-scale geodiversity for biodiversity research and management. *Journal of Applied Ecology* 59: 1756–1768. https://doi.org/10.1111/1365-2664.14183
Article II	Salminen H, Tukiainen H, Alahuhta J, Hjort J, Huusko K, Grytnes J-A, Pacheco-Riaño LC, Kapfer J, Virtanen R & Maliniemi T (2023) Assessing the relation between geodiversity and species richness in mountain heaths and tundra landscapes. *Landscape Ecology* 38: 2227–2240. https://doi.org/10.1007/s10980-023-01702-1
Article III	Salminen H, Huusko K, Tukiainen H, Varnajot A, Alahuhta J, Saviranta M, Hjort J & Maliniemi T (2025) The effects of land use on fine-scale geodiversity: Ski resorts as an example. *Science of the Total Environment* 988: 179830. https://doi.org/10.1016/j.scitotenv.2025.179830

The three original articles are available in the appendices of the printed version of this thesis, and they are reprinted under the CC-BY 4.0 Creative Commons Attribution license.

Author's contributions

Article I Salminen designed, led and conducted geodiversity fieldwork with contributions from Kiilunen and Snåre. She conducted the analysis with Maliniemi and Tukiainen and contributed to writing the original manuscript.

Article II Salminen contributed in planning the study design and designed, led, and conducted geodiversity fieldwork. Salminen led the analysis of the data with contributions from Maliniemi and Pacheco-Riaño. Salminen led the writing of the original manuscript, which was reviewed by all authors.

Article III Salminen conceived the original research ideas and study designs with Maliniemi. Salminen designed, led and conducted geodiversity fieldwork. Salminen analysed the data and led the writing of the original manuscript, which was reviewed by all authors.

Overview of each co-author's contributions to Articles I–III, where bold underlined initials denote the thesis author Salminen.

Article	Idea & design	Data collection	Analysis	Writing
I	JH, TM, HT	**HS**, PK, HSn	TM, **HS**, HT	JH, TM, HT, **HS**, JK, PK, HSn, JA, TM
II	**HS**, TM, JH, JA	**HS**, KH, TM, JK, RV	**HS**, TM, LCP-R	**HS**, HT, JA, JH, KH, J-AG, LCP-R, JK, RV, TM
III	**HS**, TM	**HS**, KH, MS	**HS**	**HS**, KH, HT, JA, MS, JH, AV, TM

HS = Henriikka Salminen, JH = Jan Hjort, TM = Tuija Maliniemi, HT = Helena Tukiainen, PK = Petteri Kiilunen, HSn = Henna Snåre, JK = Jutta Kapfer, JA = Janne Alahuhta, KH = Karoliina Huusko, RV = Risto Virtanen, LCP-R = Laura Camila Pacheco-Riaño, J-AG = John-Arvid Grytnes, MS = Mikko Saviranta, AV = Alix Varnajot.

I did not use generative language models in the planning and writing of this dissertation. However, I used generative AI technology to support conducting the analyses. I take full responsibility for the content of this dissertation.

Acknowledgements

First and foremost, I was lucky to have support from three supervisors during this process. My main supervisor Janne Alahuhta. Thank you for encouraging me to apply for a PhD position in the first place. You provided me with tools to begin with and encouraged me to trust my gut with the decisions during the process. Tuija Maliniemi, I have learnt from you not only the craft of science but also what it means to be a researcher. Thank you for infecting me with the love of fieldwork and explaining repeatedly the ecological methods. Helena Tukiainen, thank you for supervising by example. You have been guiding me towards the next steps gently and pushed me to focus on the essentials. You also encouraged me to take an active part in the community and to meet new people.

I would like to sincerely thank all my co-authors: I have learned a lot from each of you. Working with you has been smooth and fruitful. My sincerest thanks for the field team Karoliina Huusko, Henna Snåre and Petteri Kiilunen for being in the field with me in 2020 after a rough start with this thesis. I wholeheartedly enjoyed the time we shared laughing and overcame difficulties, such as missing a freezer, which is why I also want to thank the local grocery store S-market Salla.

I also want to thank two pre-examiners, Senior Lecturer Melinda McHenry and Dr. Sonja Wipf, who took their time to scrutinize and carefully assess this thesis. Your suggestions and insightful comments greatly improved this thesis. I am grateful to Associate Professor Carina Hoorn who accepted the invitation to act as my opponent during the defence. I am looking forward to our discussion. Thank you to my follow-up group, Docent Harri Antikainen, Dr. Sanna Varanka, and Dr. Outi Kulusjärvi for your support and advice during the process.

This dissertation was conducted in the Geography Research Unit at the University of Oulu. Thank you for the support and structures that have enabled this dissertation to actualize. Thank you to unit leaders Jarkko Saarinen and Jan Hjort. I would like to extend my gratitude to the University of Oulu Graduate School, Geography Research Unit, and Suomalainen Konkordia-liitto for funding my doctoral training, research visit and conference trips. Also, thank you to Professor John-Arvid Grytnes for hosting my research visit to the University of Bergen. Heartfelt thanks for Kilpisjärvi Biological station and their staff for their warm welcomes and enabling fieldwork in remote locations.

Warmest thanks to all of my colleagues in Physical Geography Research Lab, Geography Research Unit and colleagues beyond these corridors. I have had wonderful discussions in unit's coffee room, at research stations, spent evenings with fellows who are up for fun events ranging from handicraft nights to potato-themed food fests. I am delighted that I have made some true friends. Special thanks to Maija and Marika, whom we share a path that started from our very first day in university. I have learned a lot from your example, and I am grateful of our friendship. To friends outside geography circles; I can't thank you enough for all pizza nights, gig company, casual football, and other gaming gatherings. You have helped a lot more than you might have imagined.

I want to thank my family. You have patiently listened to my stories, frustrations and happy news from academia; probably handful of too many. You reminded me that there is life beyond it – and that is what matters the most. Above all, I am grateful to Heikki for supporting my endeavours and aspirations but also taking me to all kinds of adventures during.

Glossary

AIC ....Akaike information criteria
CNS ....Conserving Nature's Stage
DEM ....digital elevation model
Georichness ....number of geofeatures on a defined area such as a study plot
GLM.................generalized linear model
GLMM............generalized linear mixed-effects model
IDH ....Intermediate Disturbance Hypothesis
NMDS ....non-metric multidimensional scaling
TWI ....topographic wetness index

1 Introduction

Fine-scale geodiversity has a crucial yet under-recognized role in supporting biodiversity and guiding sustainable land use decisions in northern environments. This thesis advances our understanding of its ecological importance and vulnerability. To date, there have been few refined methods to assess fine-scale geodiversity comprehensively (Alahuhta et al. 2020; but see Crisp et al. 2022a; de Falco et al. 2021; Kärnä et al. 2018). To address this, I present and apply a field methodology for observing fine-scale geodiversity, which forms the empirical foundation for this thesis. I then examine how fine-scale geodiversity influences plant species richness in Boreal-Arctic ecosystems and assess how tourism-related land use alters these geofeatures in Finnish Lapland.

Geodiversity is an integral part of nature's diversity (Justice et al. 2025). It refers to the variety of materials, forms, and formations of the Earth's surface and subsurface and includes the diversity of geology (bedrock and soil), geomorphology (landforms, topography, and processes), and hydrology (Gray 2013). Thus, geodiversity forms the abiotic diversity of the Earth's surface and subsurface. Geodiversity is a rather recent yet important addition to understanding and studying nature holistically (Justice et al. 2025), as nature conservation has traditionally focused primarily on biodiversity, which is the diversity of the biotic environment (Comer et al. 2015; Crisp et al 2022b; Tukiainen & Bailey 2022). Together with biodiversity and climate, geodiversity establishes the foundation for humans to exist.

Global change and the alarming decline of biodiversity are increasing pressure to better understand biodiversity patterns, protect nature and assess the impacts of environmental change from local to global scales. Northern environments are specifically at risk, with their climates warming faster than the global average (IPCC 2021; Rantanen et al. 2022). The latest assessment of The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES 2019) states that a quarter of assessed animal and plant species are threatened and 1 million species are at the brink of extinction. So far, actions aimed at halting biodiversity loss have not succeeded in reversing the negative trend (IPBES 2019), which highlights a need for new methods and approaches to improve and complement current conservation strategies.

Information on geodiversity has the potential to give us new insights and tools to change course with improved understanding, modelling, and prediction of biodiversity (Antonelli et al. 2018; Lawler et al. 2015). A positive relationship between geodiversity and biodiversity at the landscape scale has been identified in several studies (see e.g. Hjort et al. 2015; Read et al. 2020; Tukiainen et al. 2017; Tukiainen et al. 2022a), even though the relationship is context-dependent (Tukiainen et al. 2023), but due to a lack of suitable empirical data and methods, research at the fine scale has been very limited (Alahuhta et al. 2020; but see Kärnä et al. 2019; Stefanidis et al. 2023). This is a critical knowledge gap, as decisions on conservation and land use are often made locally (Wyborn & Evans 2021).

So far, there has been a general mismatch between the scales in which geodiversity research and field-based biodiversity inventories have been made (Alahuhta et al. 2020). For instance, vegetation assessments are generally done at fine scales, as geodiversity is often assessed at a coarser resolution. In biodiversity research, fine-scale species data have proven to be detailed and context-specific, allowing accurate assessments and effective conservation strategies (Tribsch et al. 2010). Field-based biodiversity investigations frequently study the effects of abiotic drivers such as temperature, pH, or moisture while seldom addressing the complete abiotic environment (see e.g. Mod et al.

2016). Thus, fine-scale approaches in mapping geodiversity are crucial for providing the detailed, accurate data necessary for understanding not only geodiversity patterns but also the complex relationships between geodiversity and biodiversity.

The conservation strategy Conserving Nature's Stage (CNS) is based on the idea that the abiotic environment acts as a stage on which the actors – the animal and plant species – perform (Beier et al. 2015). It suggests that the more variation in the abiotic environment, the more diverse the actors on this stage are, even over time. According to the CNS strategy, geodiversity could be used to identify areas best suited for conservation and therefore mitigate the challenges posed by a changing environment in conservation planning (Beier et al. 2015; Hjort et al. 2015). In this way, information on geodiversity can complement existing conservation strategies. Conversely, it could help identify areas where land use has little impact on geodiversity or where geodiversity is resistant to the effects of land use. However, CNS strategy is developed for larger scales, and these interconnections are very little studied at fine scales.

Humans affect geodiversity in many ways as abiotic nature offers a plethora of commodities (Ibáñez & Brevik 2022). Human pressure poses a threat to geodiversity (Beierkuhnlein et al. 2025; Gray 2013), but at the same time, geodiversity is essential for societal and economic development. But at what cost? Landscape-scale studies have reported negative effects of land use on geodiversity, such as partial or complete loss of landforms, in the responses of geodiversity to land use (Kiernan 2010b; Rentier et al. 2024; Rodrigues & Silva 2012; Santos et al. 2017; Tukiainen et al. 2017). Researchers insist that geodiversity should be considered in decision-making and efforts toward sustainable development and resource use (Schrodt et al. 2019). Decision-making often happens locally, but there has been a lack of fine-scale approaches, measures and recommendations that future conservation and land use management decisions could be based on.

In this thesis I explore fine-scale geodiversity in northern Fennoscandian Boreal-Arctic environments. I will lay out the groundwork for empirical, field-based, fine-scale geodiversity research through three research articles that are included in this thesis. In Article I, I introduce a field method for observing fine-scale geodiversity. This method underpins the geodiversity data collection for all three articles within my thesis, and the collected data is then applied with ecological methods within a quantitative-qualitative framework. In Article II, I cut into geodiversity–biodiversity relationships in aiming to explain how fine-scale geodiversity is related to the species richness of three taxonomic groups (vascular plants, bryophytes, and lichens) of heathland and tundra vegetation. Further, in Article III I explore how ski tourism–related land use affects and shapes fine-scale geodiversity. Therefore, this thesis profoundly contributes to geodiversity research by examining and providing a continuum for how fine-scale geodiversity can be observed, how this new information can provide insights about vegetation patterns, and how fine-scale geodiversity is changing under human influence.

2 Geodiversity

Geodiversity is as multifaceted concept as its counterpart biodiversity; it has been defined in many ways, and the definition continues to evolve (Maliniemi et al. 2024, Tukiainen & Toivanen 2025). The concept has roots in the early 1990s, following the Rio De Janeiro Earth Summit in 1992 and the Convention on Biodiversity. In response, geoscientists recognized the need to establish an equivalent concept for abiotic diversity.

The term 'geodiversity' soon appeared in scientific literature, notably in Sharples (1993) and Wiedenbein (1993) (Gray 2013). The most used (Boothroyd & McHenry 2018) definition comes from Gray (2013), who defines geodiversity as "*the natural range-(diversity) of geological (rocks, minerals, fossils), geomorphological (landforms, topography, physical processes), soil and hydrological features. It includes their assemblages, structures, systems and contributions to landscapes.*" There has been an ongoing debate on whether to include climate or atmosphere in the definition as well (Bailey et al. 2024; Gray 2025; Parks & Mulligan 2010; Zarnetske et al. 2019). This thesis, however, uses the commonly used definition of geodiversity proposed by Gray (2013), which does not include climate as part of geodiversity.

Geodiversity can be studied quantitatively (see e.g. Santos et al. 2017; Toivanen et al. 2024), qualitatively[1] (see e.g. Hjort et al. 2015; Panizza 2009; Santos et al. 2019) and qualitative-quantitatively (see e.g. Tukiainen et al. 2017; Zakharovskyi et al. 2024). Variety of methods to assess geodiversity are increasingly being developed and used (Boothroyd & McHenry 2019; Crisp et al. 2021; Zwoliński et al. 2025), mostly focusing on broader scales (e.g. Carríon-Mero et al. 2022; Santos et al. 2017). So far, geodiversity has been assessed quantitatively mainly with grid-based methods and geospatial data (Crisp et al. 2021), which has proved to be useful in a plethora of studies conducted in regional, landscape and global scales (e.g. Bétard & Peulvast 2019; Carrión-Mero et al. 2022; Dias et al. 2021; Pereira et al. 2013; Santos et al. 2017; Toivanen et al. 2024). The main objective in these studies has been to produce and utilize geodiversity indices in geodiversity research or geodiversity–biodiversity research (see e.g. Crisp et al. 2021; Vieira et al. 2025). However, quantitative studies from finer scales have been lagging due to lack of data collection methods (Alahuhta et al. 2020). In this thesis, I am focusing on fine-scale geodiversity by using qualitative-quantitative methods.

From the beginning of the use of the term, scientists have had the goal of assessing geodiversity systematically. Geodiversity can be observed hierarchically across the scales, from landscapes to distinct geodiversity elements and processes, and all the way to small particles such as minerals (Hjort et al. 2024; Serrano & Ruiz-Flaño 2007). In the field, geodiversity can be observed through its elements (i.e. geofeatures) that are distinct geological, pedological (soil), geomorphological, or hydrological features (Bailey et al. 2017; Hjort et al. 2024; Serrano & Ruiz-Flaño 2007). The classification system published by Hjort et al. (2024) presents a hierarchically structured taxonomy, starting from the general components of geodiversity and continuing into detailed levels, and forms a basis that can be applied in observing and quantifying geodiversity especially in landscape and finer scales. In this thesis, I use the third and fourth levels of Hjort et al.'s (2024) taxonomy of geodiversity.

Quantification of geodiversity has recently made substantial headway. It has been proposed that incorporating methods and concepts from ecological research might prove useful in geodiversity research as well. For example, using alpha and beta diversity frameworks for geodiversity has been proposed by Tukiainen et al. (2022a) as have statistical methods primarily designed for ecological research (Benito-Calvo et al. 2009; Ferrer-Valero et al. 2019). Most geodiversity quantifications have focused on the geodiversity of individual sites or areas using different geodiversity indices, or simple richness measures. The latter can be considered as indicating alpha geodiversity, which

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1 The term 'qualitative' in this thesis has evolved from ecological traditions, where it is precepted and applied differently than in human sciences. In this juxtaposition we could argue whether it is appropriate to use the term 'qualitative' instead of the term 'descriptive.'

is the geodiversity of a local site, or gamma geodiversity, which is the geodiversity across sites within a larger region (Crisp et al. 2021; Tukiainen et al. 2022a). In fine scales, mostly alpha geodiversity has been explored (Kärnä et al. 2018). Beta geodiversity metrics, in turn, quantify geodiversity between sites based on the dissimilarities of geofeatures (elements of geodiversity) but have remained generally less utilized than alpha- or gamma-level indices (but see Erikstad et al. 2022; Ibáñez et al. 1995; Tukiainen et al. 2022a).

2.1 Geodiversity information at fine scales – what has been missing?

Qualitative geodiversity and geoheritage research have widely used finer scales in their geodiversity assessments (Zwoliński et al. 2025). Quantitative research and observations on geodiversity, however, have been mainly focusing on landscape, regional and global scales. Studies from finer scales have been missing mainly because of a lack of existing datasets but also because of the scarcity of existing, transferable, field-validated methods to gather data suitable for quantitative fine-scale studies in terrestrial environments (Crisp et al. 2022a; Tukiainen et al. 2023). Fine-scale research requires accurate data with a spatial resolution of even under one metre. This has not yet been obtained systematically through traditional remote sensing of all aspects of geodiversity. For instance, it is hard to assess soil geofeatures from drone or satellite imagery, even though topographical information can be obtained in high resolutions. Kärnä et al. (2018) assessed fine-scale geodiversity in river habitats by observing streamflow diversity. De Falco et al. (2021), on the other hand, observed geodiversity in semi-arid habitats through topographical variation.

Geodiversity can be observed at different levels (Hjort et al. 2024) of which the ‘particle’ level is the most detailed. It includes atoms, molecules, and energy processes (see Serrano & Ruiz-Flaño 2007). However, it is difficult to obtain and seldom applicable to biodiversity research except for research on soils that is extensively researched. The next level, which is the ‘elements of geodiversity,’ includes specific geofeatures of geology, geomorphology, and hydrology (Article I; Figure 1; Hjort et al. 2024; Serrano & Ruiz-Flaño 2007). This level provides fruitful ground for an efficient and applicable field method to collect geodiversity information for geodiversity research, such as geodiversity–biodiversity investigations. Within this framework, geological (including pedological) elements include different rock and soil types. Geomorphological features and processes, which contribute to topography as well, include, for example, weathering, aeolian, and mass wasting processes, to begin with. In addition, hydrological features include standing and flowing waters on and under the ground.

Widening geodiversity research into finer scales offers invaluable information about abiotic nature in our immediate surroundings. Fine-scale data about geodiversity are useful for strengthening understanding of the phenomena, such as geodiversity–biodiversity relationships, that we observe from larger (landscape and regional) scales. This information is invaluable for decision-makers, as land management and nature conservation plans are usually made in fine-scale settings (Wyborn & Evans 2021). But it also serves the idea of using the appropriate methods and scales for particular purposes (Chaplin-Kramer et al. 2022), as knowledge of geodiversity is needed from across scales, from global to local. Holistic geodiversity explorations complement the already utilized fine-scale measurement of topographical and environmental heterogeneity that are often used in biodiversity studies to describe abiotic variability (e.g. Opedal et al. 2015).

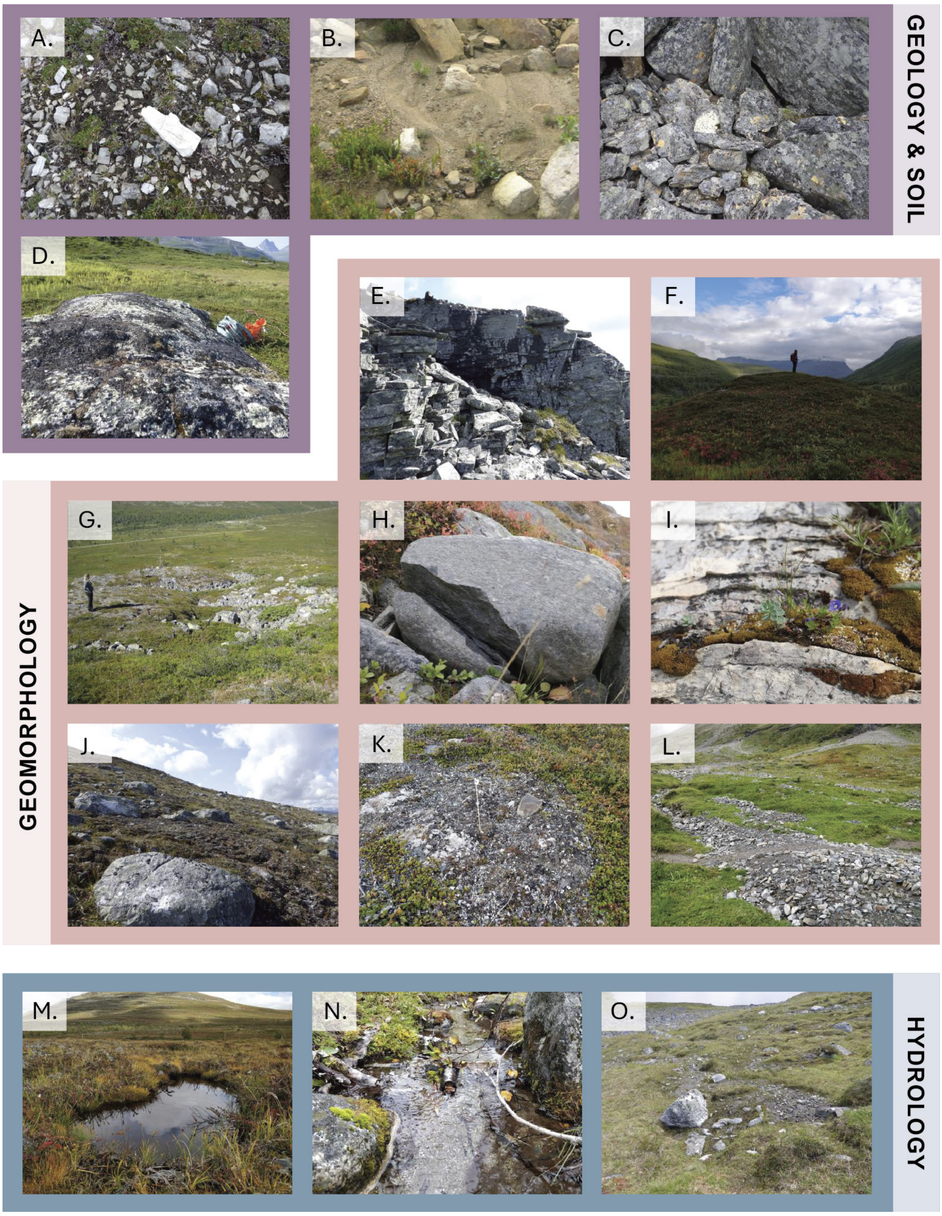

Figure 1. Example photos of different geofeatures from fine scale: (A) diamicton/unsorted material, (B) sand, (C) boulders, (D) exposed bedrock, (E) cliff/escarpment, (F) glasigenic deposition as in moraine hummock, (G) glaciofluvial erosion, (H) physical weathering, (I) chemical weathering, (J) slow mass wasting as in solifluction, (K) cryogenic process as in cryoturbation, (L) quick mass wasting, (M) pond, (N) stream, (O) spring. Photos are from northern Finland and northern Norway. Photos: Henriikka Salminen.

3 Geodiversity–biodiversity relationships

A heterogenic abiotic environment (high geodiversity) provides a foundation to resources, microtopography, and microclimate and thus a diversity of niches for different species to exist (Kerr & Packer 1997; Stein et al. 2014). This thought has raised an idea of the Conserving Nature's Stage conservation strategy (CNS, Beier et al. 2015; Lawler et al. 2015) where the abiotic environment is seen as a stage for different species, or 'actors,' to exist and thrive. In CNS strategy, areas with high geodiversity should host high biodiversity (Beier et al. 2015). Geodiversity is seen as a buffering agent that provides resilience against biodiversity loss (Gordon et al. 2022), as it is considered temporally more stable than biodiversity (Lawler et al. 2015). In the context of global biodiversity loss (IPBES 2019), information about drivers that affect biodiversity patterns is crucial, and geodiversity is one driver that is largely unexplored to date.

An increasing number of research studies have been published on the relationship between geodiversity and biodiversity (Tukiainen et al. 2023). Most of these have been done on landscape or regional scales (De Falco et al. 2021; Toivanen 2024; Toivanen et al. 2019; Zarnetske et al. 2019). They generally show a positive relationship between geodiversity and biodiversity and thus provide support for the CNS strategy. In addition, Crisp et al. (2022a) have proposed the idea of omnidiversity, where geodiversity is assessed with GIS-based methods together with biodiversity to achieve an overall estimate of the diversity of a site. Also, adding geodiversity into species richness modelling has been proven to improve the models (Hjort et al. 2012; Read et al. 2020; Tukiainen et al. 2017) especially towards finer resolutions in a landscape scale (Bailey et al. 2017). But species show idiosyncrasies towards geodiversity variables, highlighting species-specific interactions with the environment (Bailey et al. 2018; Gerstner et al. 2024). Research about fine-scale geodiversity's relationship with biodiversity is still scarce (but see Crisp et al. 2022b; Kärnä et al. 2018; Tukiainen et al. 2023) but much needed, as biodiversity patterns are heavily scale-dependent (Crawley & Harral 2001), which highlights the need to expand geodiversity research into finer scales.

However, it is not a one-way relationship where geodiversity affects biodiversity (Beierkuhnlein et al. 2025; Gray 2013; Tukiainen et al. 2023). Mutually, biodiversity affects geodiversity. For example, a variety of minerals require oxygen in their formation process, and oxygen is produced by vegetation (Hazen & Morrison 2022). Furthermore, vegetation regulates soil acidity (Augusto et al. 2002) and holds moisture (Jaroszynska et al. 2013) that, for example, induces weathering on rocks and the formation of soils (see e.g. Billings 1973). Vegetation is crucial for decomposition and the carbon cycle (Cahoon et al. 2012). In addition, vegetation regulates evapotranspiration and moisture conditions (Robinson et al. 2018; Seaton et al. 2019), which further affects geomorphological processes and landforms such as cryoturbation or peat formation (French 2017).

Geodiversity–biodiversity research is very relevant in high-latitude and Arctic-alpine ecosystems, which are especially at risk (Aronsson et al. 2021). These areas experience the effects of global change faster than any other region in the world (IPCC 2021). Arctic-alpine environments are suitable for investigating fine-scale geodiversity methods, as there earth surface processes are among the main drivers of species richness (le Roux & Luoto 2014) and plant community traits (Kemppinen et al. 2022). This lays the foundation for the importance of fine-scale geodiversity research in Boreal-Arctic environments, which I cover in this thesis.

Apart from geodiversity, there are several drivers and mechanisms that affect fine-scale biodiversity patterns in these environments. Even though geodiversity *per se* has not been explored as a causal indicator, for example, microtopographical variation has been studied, as it creates cooler shades, windswept mounds, and warmer depressions (Kumar et al. 2006; Opedal et al. 2015; Pajunen et al. 2008). In addition to small-scale ones, large-scale variables like macroclimate, such as sum of growing degree days (GDD) and expected amount of solar radiation, are related to species richness in northern environments (Bueno de Mesquita et al. 2019; Giaccone et al. 2019; Niittynen et al. 2020). Further, studies have shown that nutrient levels and the presence of certain elements, such as the amount of calcium, which affects pH (Gough et al. 2000; van der Welle et al. 2003), and soil moisture are important drivers of species richness in Arctic-alpine environments (Kemppinen et al. 2019).

In addition to the abiotic determinants, there are several biotic drivers in Fennoscandia that affect species richness patterns. Among biotic interactions, reindeer grazing (Kaarlejärvi et al. 2017) and the abundance of dominant species, especially crowberry (*Empetrum nigrum* ssp. *hermaphroditum*), regulate species richness in Arctic-alpine heaths of Fennoscandia (Bråthen & Ravolainen 2015; le Roux et al. 2014; Mod et al. 2016). Despite the evidence of a positive geodiversity–biodiversity relationship from landscape-scale studies (De Falco et al. 2021; Toivanen 2024; Toivanen et al. 2019; Zarnetske et al. 2019), there is not yet comprehensive empirical research done on fine-scale geodiversity's relationship to species richness alongside other environmental drivers, which I explore in this thesis.

4 Geodiversity under land use change

Throughout history, geodiversity has been intertwined with the development of civilizations. Each of the stone age, bronze age, and iron age to the information age, also referred to as the silicon age, reflects a defining reliance on specific abiotic resources. Human societies have always depended on geodiversity, using Earth-derived materials at an accelerating pace and thereby altering geodiversity. The goods and services that geodiversity is providing humans are called geosystem services (van Ree & van Beukering 2016) and they are part of the ecosystem services that are directly derived from the abiotic nature of our planet (CICES 2025). These services include fresh water, building materials, rare minerals, and many more (Gray 2013). Research about geodiversity's relevance for societies has been conducted from a multiplicity of angles, such as ecosystem services (Alahuhta et al. 2018; Bailey et al. 2024), geosystem services (van Ree et al. 2017), nature conservation (Tukiainen & Bailey 2022), tourism (Chakraborty 2022), and human health (Alahuhta et al. 2022; see also Kubalikova et al. 2023). Thus, geodiversity has qualitative dimensions and can be assessed qualitatively.

In many ways the human impact on geodiversity is permanent, as geological features are destroyed completely, for example through mining activities or in quarries (Kiernan 2010a). Natural World Heritage sites that have been listed in category VIII Earth are deteriorating due e.g. to tourism pressure and climate change effects (Osipova et al. 2020). At the landscape level, studies have shown the negative impact of land use on geodiversity (Kiernan 2010a; Rentier et al. 2024; Rodrigues & Silva 2012; Santos et al. 2017). Also, Tukiainen et al. (2017) showed that greater human disturbance corresponds to lower contributions to species richness. In this thesis, I approach human impact on fine-scale geodiversity through tourism land use, and more specifically through a ski tourism framework (Article III). While studies on the relationships between geodiversity and tourism, and especially on how geodiversity promotes tourism activities, have been conducted (see Gray 2018; Jia et al. 2023; Newsome & Ladd 2022), there is a lacuna in studies of how tourism activities holistically affect fine-scale geodiversity (Anougmar et al. 2024).

Topographically interesting landscapes are one motivation when tourists choose their destinations (Gray 2019), which actualizes in high latitudes in the form of ski tourism and related activities. Increasing demand for recreational activities and the growth of the tourism industry have led to an expansion of land use (Williams & Shaw 2009). It significantly contributes to biodiversity loss, for instance, by the clearance of land for infrastructure and pollution (Hall 2015). Tourism has been reported to alter natural landscapes and has negative effects on vegetation, wildlife and, soils in tourist areas at high latitudes (Tolvanen & Kangas 2016). While the effects of ski resorts on biodiversity (e.g. Casagrande-Bacchiocchi et al. 2019; Maliniemi & Virtanen 2021; Tolvanen & Kangas 2016; Wipf et al. 2005), on soils (Buttler et al. 2023; Casagrande-Bacchiocchi et al. 2019) and on snow properties (Isselin-Nondedeu & Bédécarrats 2007; Rixen et al. 2004) have been studied across Arctic-alpine environments, comprehensive research on geodiversity, apart from the soils, remains non-existent (Chakraborty 2022).

While geodiversity is considered the stage for biodiversity (following the idea of CNS strategy) that provides resilience against human impact on nature (Beier et al. 2015; Gordon et al. 2022), it is surprisingly overshadowed by biodiversity in conservation actions (Chakraborty & Gray 2020; Crofts 2018; Matthews 2014). Geoconservation aims to conserve geodiversity because of its intrinsic, ecological and geoherital value (Prosser 2013; Sharples 2002) to raise awareness, assess, evaluate, interpret, and in the end conserve geodiversity for future generations (Brilha 2016, 2025). Recently, geoconservation has gained more attention, and even the International Union for Conservation of Nature (IUCN) has recognized its importance (Crofts et al. 2020). The Global Geopark Network has been promoting the conservation of geodiversity and geological heritage and there are currently 229 UNESCO Geoparks around the world (UNESCO 2025). In addition, many national and regional conservation frameworks include geodiversity from different aspects, such as in Tasmania (Department of Natural Resources and Environment Tasmania 2024) or in the United Kingdom (Evans et al. 2023). However, more comprehensive conservation planning is needed to integrate geoconservation principles and methods into the management of all protected areas (Gordon et al. 2021). In addition, standardized, reproducible research practices are needed to integrate geodiversity into broader conservation and policy frameworks (Toivanen 2024), but at finer scales, these are lacking.

5 Aims

The main aim of this thesis is to improve our understanding of fine-scale geodiversity, its importance to biodiversity and its vulnerability to land use in northern environments through empirical research. To achieve this, I first introduce the methodology for observing fine-scale geodiversity in the field that was used to collect the data for all the Articles (I–III; Hjort et al. 2022; Salminen et al. 2023a, 2025) in this thesis. I further explore the relationship between fine-scale geodiversity and plant species richness in boreal-Arctic heath and tundra environments (Article II) and study how tourism-related land use affects fine-scale geodiversity in Finnish Lapland (Article III; Figure 2). In Articles II–III, I implement ecological methods and concepts recently adapted for geodiversity research to assess fine-scale geodiversity both quantitatively

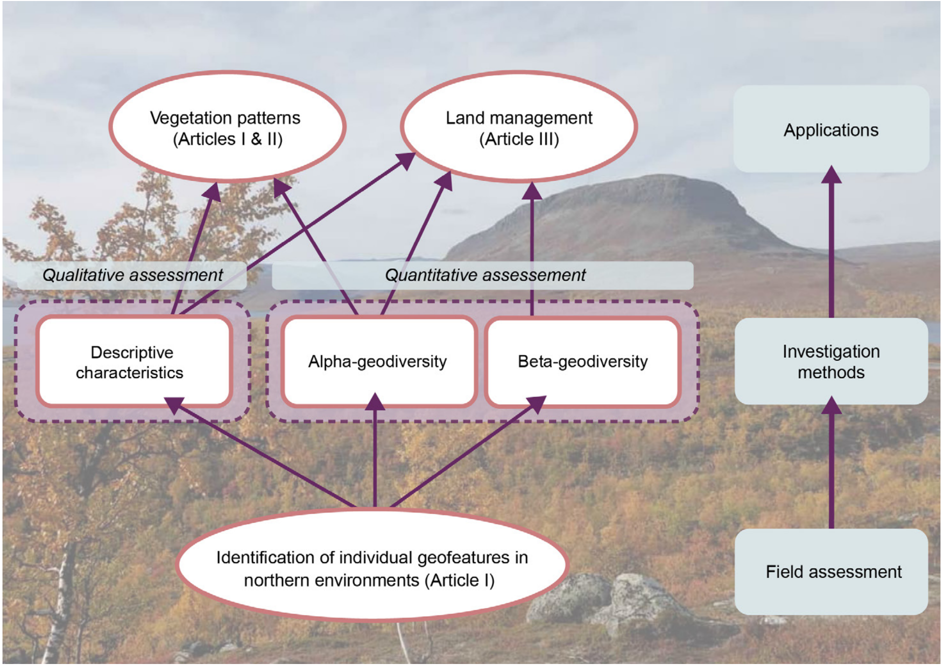

Figure 2. The general outline of this thesis and which Articles (I, II, or III) relate to each part.

and qualitatively. Finally, I propose ideas and thoughts on what kind of added value fine-scale geodiversity brings to nature conservation and land use management.

A lack of methodologies has lagged research of fine-scale geodiversity (Alahuhta et al. 2020). Grid-based methodologies that utilize GIS-based data as the basis of geodiversity calculations are not suitable for empirical fine-scale studies, as the available data are not accurate enough. This has prevented us from utilizing geodiversity information in other contexts, such as nature conservation and land use planning. To fill in this gap, a comprehensive field assessment method yearned to be developed. Fine-scale geodiversity research serves as an essential source of information for practitioners engaged in conservation and land management applications. Therefore, I ask the following question:

Q1: How can fine-scale geodiversity be observed and quantified? (Articles I, II & III)

We are currently experiencing a dramatic decay of biodiversity, and conservation efforts have not sufficed to turn that trend around (IBPES 2019; Secretariat of the Convention on Biological Diversity 2020). CNS strategy has been proposed to strengthen already existing conservation strategies (Beier et al. 2015; Schrodt et al. 2019; Tukiainen & Bailey 2022), and there is a growing amount of research done about geodiversity–biodiversity relationships in larger scales (see Toivanen et al. 2019, 2024; Zarnetske et al. 2019). However, we still lack empirical studies that test the hypothesis of geodiversity supporting biodiversity in fine scales (Alahuhta et al. 2020; but see Kärnä et al. 2018 in stream environments).

Similar to biodiversity, geodiversity too is affected by global change and human activities. This creates a threat to geodiversity: for example, areas with exceptional geodiversity elements attract tourists, which puts geodiversity at risk (Chakraborty 2020). Although the topic is highly relevant, the impact of land use on fine-scale geodiversity has not been studied quantitatively. In this thesis, I will utilize the data which I collected in the field in two applications: in geodiversity–biodiversity research, and in studying the impact of land use on fine-scale geodiversity. Therefore, two questions follow:

Q2: How does fine-scale geodiversity relate to vegetation patterns in boreal-Arctic heathlands and tundra? (Articles I & II)

Q3: How does land use in ski resorts affect fine-scale geodiversity? (Article III)

To conclude the findings from the three research articles, I will discuss what practical applications and possible recommendations this thesis, and more broadly, fine-scale geodiversity research might offer for policymakers, conservationists, practitioners, and societies:

Q4: What information on fine-scale geodiversity measurements can offer for conservation and land management? (Articles I, II, & III)

6 Study area

All the study plots in this thesis are located in the open fells[2] of northern Finland and Norway (Figure 3). The bedrock of this area is mostly acidic and consists of Precambrian and Palaeozoic sedimentary rocks in the north-west (Lehtovaara 1995), Precambrian granulites in the north, Paleo-proterozoic quartzes and volcanic rocks in the central areas, and Archaic gneisses in the southernmost areas (Geological Survey of Finland 1997; Odland 2014). The bedrock was shaped by ice age forces, resulting in a rounded topography. Combined with its northern position, this has led to diverse periglacial landforms, fluvial processes, and frost action (French 2017). Soils in the area are thin, mainly felsic tills, and poorly developed due to the constraints of cold climate; podzols dominate in forested areas, while Boreal-Arctic heaths and tundra often feature poorly developed soils or exposed bedrock (Geological Survey of Finland 2010). Climate varies from oceanic to subcontinental conditions (Haapasaari 1988; Rantanen et al. 2023).

Vegetation on all the study sites is classified as oligotrophic open heathland and tundra vegetation, both dominated by dwarf shrubs such as *Empetrum nigrum*, *Vaccinium myrtillus*, *Vaccinium vitis-idaea*, *Betula nana,* and *Calluna vulgaris* (Table 1). Moreover, there is a high abundance of bryophytes (e.g. *Dicranum* spp.) and lichens (e.g. *Cladonia* spp., Haapasaari 1988; Maliniemi et al. 2018). Therefore, the vegetation is comparable to the European nature information system (EUNIS) classification categories S1 Tundra and S2 Arctic, alpine and subalpine scrub (Chytrý et al. 2020; EUNIS terrestrial habitat classification 2021).

2 Fells are low-lying mountains in northern Fennoscandia and northern parts of the British Isles that have been rounded by past glacial erosion. They have treeless, Boreal-Arctic heaths on their summits.

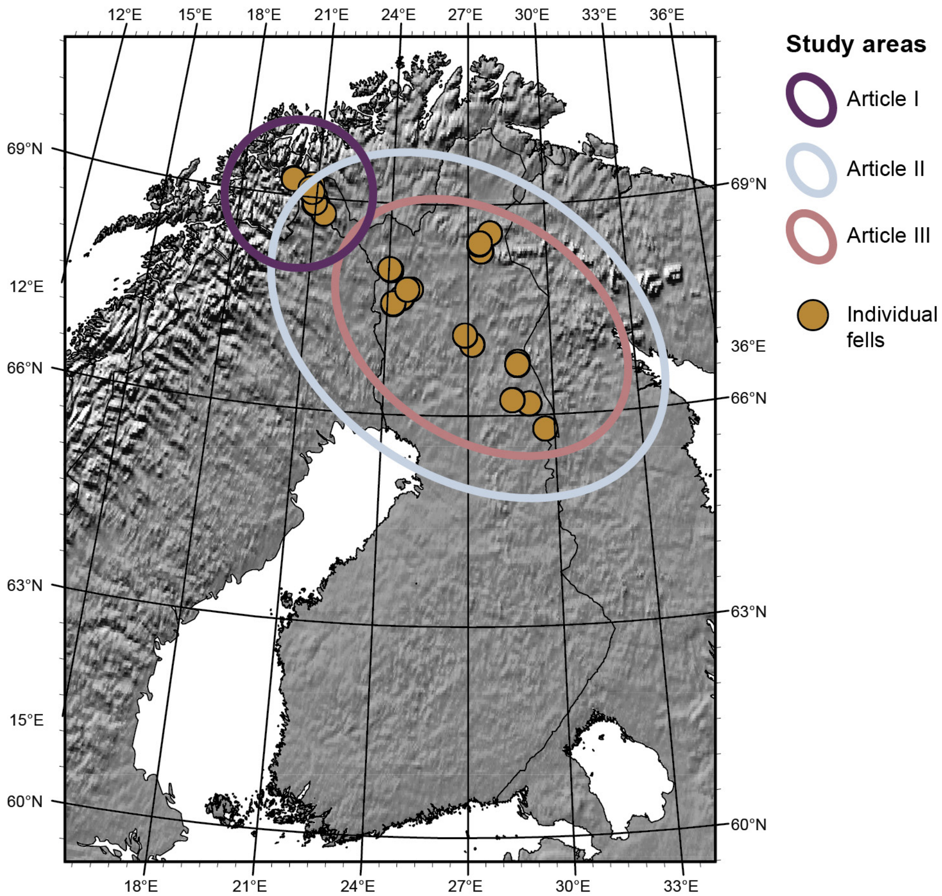

Figure 3. Map of the study plot locations in northern Finland and Norway, included in Articles I–III. Individual fells are marked with orange dots, each including three to twelve independent study plots. Baselayer: Runfola et al. (2022).

Table 1. Number of study plots in each research paper and how the plots are grouped in the study settings.

Article	Total N	Plot type	Groups
Article I	76	Oligotrophic, open heaths	Deciduous shrubs dominated, n = 36
			Evergreen shrubs dominated, n = 40
Article II	165	Oligotrophic, open heaths	Isolated, boreal, low-lying mountain tops, n = 44
			Sporadic mountain tundra, n = 58
			Continuous mountain tundra, n = 63
Article III	131	Oligotrophic, open heaths	Undisturbed, n = 47
			Semi-disturbed, n= 39
			Disturbed, n = 45

6.1 Article-specific study designs

Article I presents a study setting from north-western Finland and Norway with 76 study plots (Table 1). Plots were divided into two groups representing sites dominated by deciduous shrubs or evergreen shrubs (Figure 4a–c). Study plots in Articles II and III are dispersed across treeless mountain heaths and tundra areas in northern Finland, from southernmost, undulating, isolated treeless uplands in Northern Ostrobothnia to the more continuous mountain tundra landscapes of Finnish Lapland (Figure 3; 4d–i; Table 1). Article II has a total of 165 study plots and Article III a total of 131. The plot locations are based on old vegetation data (Haapasaari 1988), and as such data partly overlap among the three articles.

In Article II, the study area is divided into three regions based on their latitudinal position and differences in species pools, climate conditions, and grazing pressure, which all affect the characteristics of oligotrophic heaths and tundra (Figure 4d–f). The plots are unaffected by land use and can be described as being in their natural state. The first region is isolated northern boreal mountain tops, that are characterized by small open heaths on top of the fells, with boreal treeline ecotone nearly creeping to the top (Figure 4d). The second region consists of larger fell areas with more widely distributed

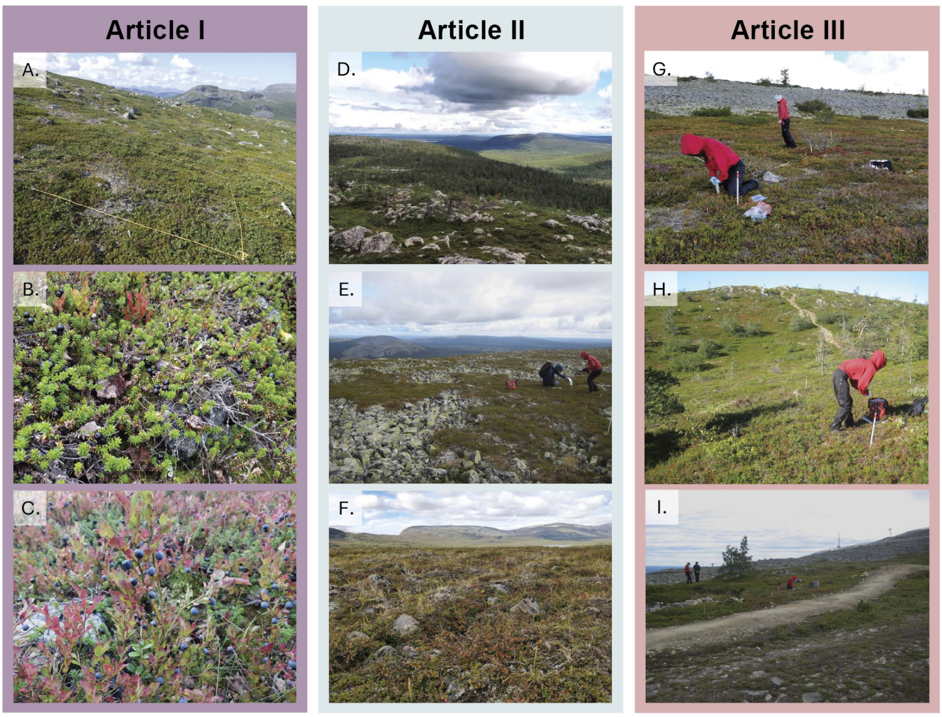

Figure 4. Study plot classifications of all three articles. Article I, violet panel at the left: (A) typical study plot on oligotrophic Boreal-Arctic heath with vegetation plot marked with yellow string. (B) evergreen shrubs (*Empetrum nigrum*) and (C) deciduous shrubs dominated (*Vaccinium myrtillus*, *Betula nana*) the vegetation type, respectively. In the middle, Article II with classifications based on natural characteristics: (D) isolated mountain tops, (E) sporadic mountain tundra, and (F) continuous mountain tundra. On the right, the land use classes used in Article III, light pink panel: (G) undisturbed, (H) semi-disturbed, and (I) disturbed. Photos: Henriikka Salminen.

open heaths, still surrounded by boreal forests (Figure 4e). The third region is more continuous oroarctic mountain tundra where the landscape is mostly open heaths and with mountain birch (*Betula pubescens* ssp *Sczerepanovii)* forming the treeline (Figure 4f).

In Article III, the study plots are divided into three classes based on their land use intensity (Figure 4g–i). Undisturbed plots represent natural state and are the only ones that are not in ski resorts or have any tourism-related land use nearby (Figure 4g). Semi-disturbed plots have some human disturbance on or near the plots, caused by tourism (mainly hiking paths, Figure 4h). Disturbed plots are directly and heavily impacted by tourism-related land use and situated, for example, directly or right next to ski slopes or other infrastructure (Figure 4i). The classification into three land use classes was done visually in the field during the vegetation mapping and is based on methodology in Kontula and Raunio (2019).

7 Materials and methods

In this chapter, I first present the field method for assessing fine-scale geodiversity (Article I) and the geodiversity data that were collected for this thesis, followed by a description of the vegetation data used in Articles I and II. I will also introduce other environmental variables and data that was used in Articles II and III. In addition, I briefly describe the statistical analyses that were used to analyse fine-scale geodiversity (Articles I, II, & III), geodiversity–biodiversity relations (Article I & II), and land use effects on fine-scale geodiversity (Article III). All analyses were made with software R (R Core Team 2025).

7.1 Field method for assessing fine-scale geodiversity

In response to the shortage of empirical fine-scale geodiversity data, Article I presents a field-based approach for its systematic assessment. The method we developed uses simple and accessible presence-absence sampling to define which individual geofeatures are observed in study plots in Boreal-Arctic tundra areas. It uses a classification system that is adjusted to northern environments (Hjort & Luoto 2010; Hjort et al. 2012, 2015). The range of geofeatures in a specific study area is defined before going to the field, and the identification of geofeatures within each study plot is based on them (see the predefined geofeatures listed in Appendix 1).

The method aims for easy usability, but at the same time it is detailed enough to capture the variability of the abiotic environment and properties of different geofeatures. The method is also versatile since it is feasible to collect an array of environmental data from the same study locations, such as species richness data and soil samples, as in this thesis. The geodiversity plot size should be adjusted in relation to all the other data collected from the study plots. Geofeatures (especially geomorphological features) affect nearby conditions for example, by regulating moisture conditions, which further affects vegetation on the plot. That is why a fine-scale geodiversity plot should be larger than the vegetation plot. The possibility of GPS location error or permanent marking of the plot should also be considered, especially if the located plots are visited multiple times for different data collections.

In the field, an observer first marks the outlines of the study plot with visible marker sticks. In this thesis the study plots are circular, but the shape can be decided to fit the study (Figure 5a). Subsequently, an observer goes through the study plot carefully and observes the presence of predefined geofeatures that can potentially be found in the study area. A hand corer can be used to determine geological geofeatures. At this level of observation (levels 3–4 in Hjort et al. 2024), the field investigation on a Boreal-Arctic heath takes about 20 to 30 minutes after getting used to the assessing. After field observations, the data can be complemented with high-resolution digital elevation models (DEMs) that are processed into hillshade maps, as several glaciogenic and glaciofluvial geofeatures may not be as apparent in the field but are detectable from the DEM. In this thesis, I used a DEM in 2 m resolution (National Land Survey of Finland 2024).

As a result, qualitative-quantitative geodiversity data collected from the field include a list of all geofeatures found from each study plot but also the absences of geofeatures that are known to be typical for the area of each plot. These data can be used in purely quantitative studies by, for example, summing geofeature observations of the plot and thus obtaining the sum of different geofeatures – georichness (Tukiainen et al. 2022a). Further, the data can be used in qualitative approaches that consider the individual geofeatures and their properties.

Fine-scale geodiversity data for this thesis were collected in summer 2020 from all the study plots (N =220) by following the developed method and from which the different samples for each article were made: Articles I (N = 76), II (N = 165), and III (N = 131). We aimed to observe 34 geofeatures that are present in open Boreal-Arctic heaths and tundra (Figure 1; Figure 5a; Appendix 1). The assessment was done from study circles with three radii (5 m, 10 m, and 25 m respectively) in all of the study plots. Circles of all radii lengths were used in Article I and only those with a 5 m radius in Articles II and III. I led the field team, and Henna Snåre and Petteri Kiilunen worked as field assistants.

7.2 Vegetation data

The vegetation plot data that were used in Articles I and II were collected from oligotrophic mountain heaths and tundra in 2013–2020 (Maliniemi et al. 2018; 2025), and the plot locations are based on old data from the 1960s (Haapasaari 1988). The plots were placed on sites that describe a typical oligotrophic heathland and tundra plant communities of the study area. These data are collected from 2 m × 2 m vegetation plots and include identities and percentage covers of vascular plants, bryophytes, and lichens. The total number of different taxa in Article I is 60, as only vascular plants were considered (Figure 3). In Article II, the study area was larger and also bryophytes and lichens were included in the data. Thus, the total number of different taxa in Article II is 130. All study plots in Articles I and II can be considered to present natural states and without any significant land use disturbance.

7.3 Other environmental variables

Composite soil samples were collected by Karoliina Huusko near the centre of the study plots (Figure 5) to gain explanatory variables for species richness models in Article II and for soil characteristic analyses for Article III. Soil samples were collected simultaneously with geodiversity data from the same study plot locations (N =220). The samples were extracted from the organic soil layer with a corer that has a diameter of 6 cm and from a maximum of 5 cm depth (less if thinner). From each plot, five cores were taken, one of which was from the centre and one 30 cm towards each compass point. Samples were put into separate plastic bags and kept cool during transportation, after which they

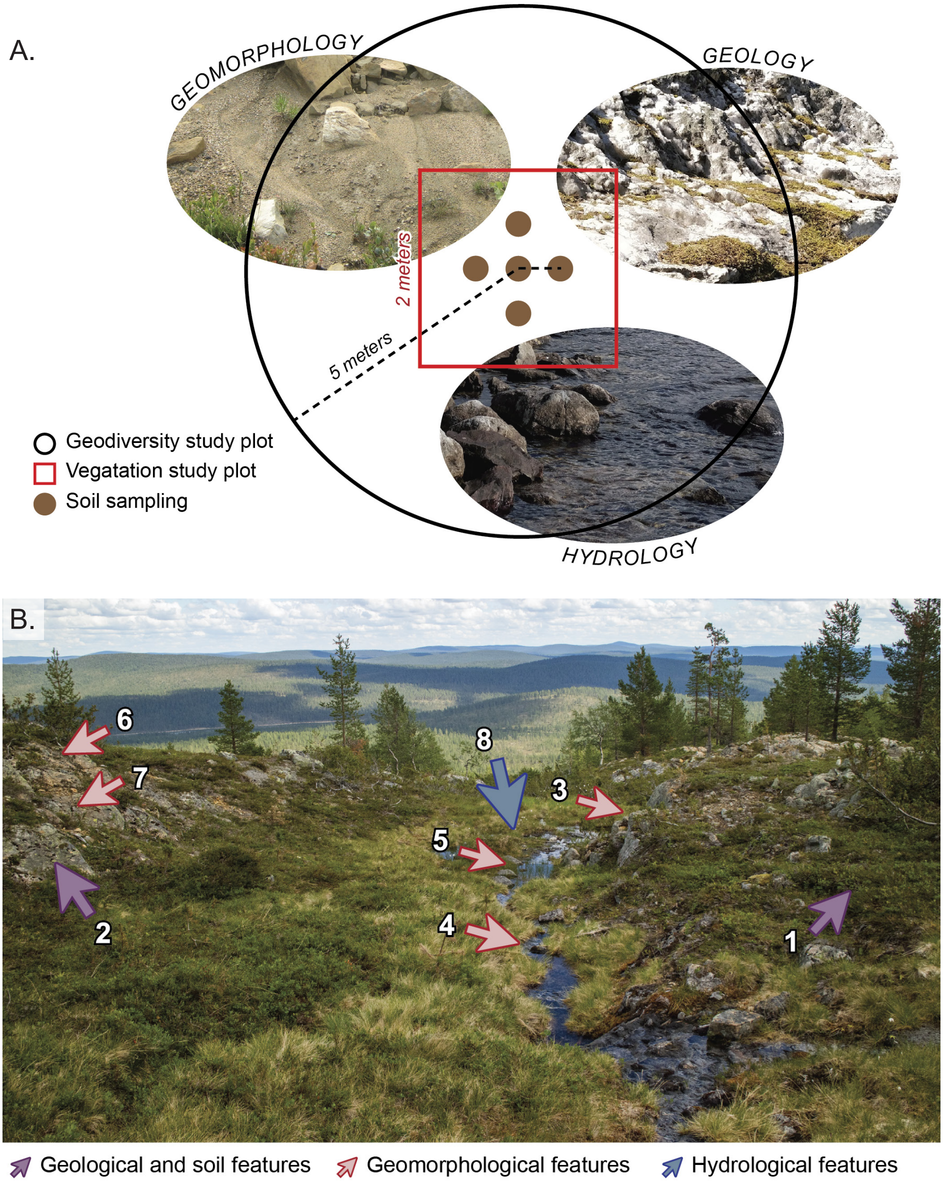

Figure 5. (A) Graph illustrating a 5 m radius study plot for mapping fine-scale geodiversity. Red square resembles the vegetation plot (2 m × 2 m) and brown circles show the soil sampling spots in relation to the centre of the plot. Photos represent geological, geomorphological, and hydrological geofeatures. (B) Example study plot from Kurupää fell in northern Finland in which are pointed out the fine-scale geofeatures we observed. The geological and soil features include diamicton (1) and exposed bedrock (2), which are indicated by purple arrows. Geomorphological features are small cliff (3), fluvial erosion (4) and fluvial deposition (5) features, aeolian erosion (6), and physical weathering (7), and they are marked with light red arrows. Of the hydrological features, there is a stream (8) marked with a dark blue arrow. Thus, in total there are eight different geofeatures within a radius of only 10 metres. Photos in panel A: Henriikka Salminen. Photo in panel B: Maija Toivanen.

were frozen (−20 °C) until analyses were carried out. Pooled soil samples were sieved through a 2 mm sieve and analysed for pH, electrical conductivity, moisture content, organic matter (OM) content, soil carbon (C), and nitrogen content, ammonium-N ($NH_{4-}N$, and soluble nutrients (Ca, Mg, K and P) (Murphy & Riley 1962; van Reeuwijk 1995; Page et al. 1982). I recognize that soil charasteristics are a part of geodiversity, but in this case I treated them as separate variables as they are traditionally used in ecological studies. In addition, they are at a different hierarchical level than the data collected in the field.

Additionally, other environmental variables were compiled for species richness models in Article II. These variables have been shown to be important for Arctic-alpine vegetation patterns (Bueno de Mesquita et al. 2018; Giaccone et al. 2019; Kemppinen et al. 2019; Kumar et al. 2006; le Roux et al. 2014; Mod et al. 2016; Opedal et al. 2015; Pajunen et al. 2008). A DEM in a 10 m resolution (NLS 2020) was used to calculate the annual potential solar radiation (kWh/m^3) with ArcGIS tool Points Solar Radiation. The same DEM was used to calculate the topographic wetness index (TWI). Further, meso-scale topographical heterogeneity was assessed visually in the field at the time geodiversity was mapped, with the variation in the surface roughness of the study plots estimated as from 1 to 10 (1 very low variation, i.e. completely flat surface, 10 very high variation). Climate data was extracted from Aalto et al. (2021) as the variable "growing degree days sum" (GDDS) in a resolution of 100 m × 100 m. Finally, the percentage cover of crowberry (*Empetrum nigrum)* was used as an independent variable, to estimate the effect a dominant allelopathic species on species richness that represents a potentially strong plant-plant interaction in the study area (Bråthen & Ravolainen 2015; Pellissier et al. 2010).

7.4 Statistical methods

A pilot study with simple analyses was conducted for Article I to support discussion about the first research question of this thesis (**Q1**; How can fine-scale geodiversity be observed and quantified?). The study question is two-phased: first the observation method is created and considered (Article I), and second, I consider how data conceived with this method can be used in various quantitative analyses (Articles I, II, & III). We first calculated frequencies of encountered geofeatures in all three articles. This gives detailed information about the fine-scale geodiversity of the study area and an overview of how fine-scale geodiversity varies within the habitats (Article I), study regions (Article II), and different land use classes (Article III). In addition, in Article I, we calculated Spearman's correlation coefficients (R_s) for the relationship between georichness of three study radii and vascular plant richness to explore which radius works best with 2 m by 2 m vegetation plots. All of the methods used in the three articles to explore fine-scale alpha and beta geodiversity are used to discuss the usability of ecological methods in quantifying fine-scale geodiversity. These methods are described in the following paragraphs with the study questions **Q2** and **Q3**.

To explore the second research question (**Q2**) of this thesis – how does fine-scale geodiversity relate to vegetation patterns – several correlative and modelling methods were utilized. As a descriptive measure, we calculated arithmetic mean values with standard error estimate for georichness value in all three articles. In Article I, we used Spearman's correlations (R_s) as well to explore if there were relationships between georichness and species richness in two kinds of habitats – those dominated by deciduous shrubs and those dominated by evergreen shrubs.

Article II dives methodologically deeper into geodiversity–biodiversity relationships by utilizing generalized linear models (GLMs). GLMs were used to describe the relationship between georichness and species richness variables (total species richness, vascular plant richness, bryophyte richness, and lichen richness). In addition to georichness, other environmental variables (amount of calcium, annual potential solar radiation, TWI, topographical heterogeneity, GDDS, and cover of *Empetrum*) were used as explanatory variables for species richness. Thus, we made univariate (georichness–species richness) and multivariate models with Poisson distributions by using R package '*glmmTMB*' (Brooks et al. 2017). Explanatory variables were first standardized with the z-score standardization method. Then, GLMs were built for each region and species groups separately using stepwise Akaike information criterion (AIC), which uses the AIC value in selecting the best model.

In addition, we used non-metric multidimensional scaling (NMDS) ordinations to investigate how the variation in the composition of the observed geofeatures correlated with vascular plant, bryophyte and lichen species richness, and total species richness. This method is traditionally used in ecological studies to describe community composition, as a beta diversity metric, but here it is used to describe geocomposition (i.e. the composition of geofeatures) as encouraged by Tukiainen et al. (2022a). NMDS plots geocomposition in a multivariate space and therefore visualizes the geocomposition in three study regions, thus revealing the differences. NMDS ordinations were made separately for the three study regions, based on observed geofeatures with Jaccard's dissimilarity as the distance metric. Correlation vectors of species richness variables were fitted into each ordination. Ordinations' goodness-of-fit were assessed using 999 permutations. NMDS ordinations were done using R package '*vegan,*' and fitting was done with R package '*goeveg*' (Oksanen et al. 2022; Salminen et al. 2023b; Von Lampe & Schellenberg 2021).

In answering **Q3**, we used the measure of georichness as the basis of alpha geodiversity calculations. Alpha geodiversity for each disturbance class was assessed using two metrics: the mean plot-level georichness and accumulation curve as an estimate of the total geofeature pool. The georichness measure was further categorized into geological, geomorphological, and hydrological richness variables. In addition, we calculated descriptive statistics for richness variables and soil variables. We used one-way analysis of variance (ANOVA) to examine whether georichness and soil variables differed among land use classes (undisturbed, semi-disturbed, and disturbed). When significant differences were detected, we applied Tukey's HSD post hoc test to identify pairwise differences. Further, we used accumulation curves to visualize the cumulative total of geofeatures within each disturbance class separately, as well as for the whole dataset. Saturation of the curve means that a sufficient number of plots has been reached to capture the variation in different geofeatures, such that adding new study plots will not further increase the number of encountered geofeatures, indicating adequate sampling size (Fischer et al. 1943).

Beta geodiversity, defined as the variation in geofeature composition among plots (i.e. geocomposition), was assessed both within and between land use disturbance classes. Beta geodiversity was quantified with Jaccard's dissimilarity index, a method commonly applied in ecological studies (Tukiainen et al. 2022a). For each disturbance class, overall beta diversity was calculated into turnover and nestedness components using the '*beta.multi*' function from the R package '*betapart'* (Brooks et al. 2017). Turnover reflects the replacement of geofeatures between sites, while nestedness indicates if the geofeatures in one site are a subset of those in a more geodiverse site (Legendre 2014). To visualize differences in geocomposition across land use levels, NMDS based on Jaccard's dissimilarity, using three dimensions (k = 3), was applied to achieve a reliable solution (stress = 0.14). Geological, geomorphological, and hydrological richness, along with all soil variables, were fitted as correlation vectors onto the NMDS ordination using the '*envfit*' function. To test for significant differences in geocomposition among land use classes, a permutational multivariate analysis of variance (PERMANOVA) using the '*adonis2*' function was performed. The analysis was based on 999 permutations, restricted within six fell regions to control the potential environmental differences between the regions. All statistical analyses were conducted in R (R Core Team 2024).

8 Results

In this chapter, I present the results of this thesis question-by-question (see Chapter 5). Table 2 shows a summary of the research questions, main findings, and contributions. In the table, the "Main findings" create the structure for this chapter, and "Contributions" guide the following Discussion section in Chapter 9.

8.1 Outcomes of observing and quantifying fine-scale geodiversity

The first research question (**Q1**) was studied in Articles I, II and III, asking: How can fine-scale geodiversity be observed and quantified? As a result, observing fine-scale geodiversity is efficient when it follows the proposed method: observing geofeatures from the study area (Article I). The geofeatures that were present were successfully observed, and no additional geofeatures were encountered that were not listed in the form. This highlights the importance of preparation before the fieldwork, e.g. getting to know the study area and listing all the possible geofeatures that could be present. In practice, we observed geofeatures by systematically following the field form. We compiled data after the fieldwork into a table that has each study plot's individual geofeatures and georichness measure (i.e. the number of different geofeatures). Respectively, we summed geological, geomorphological, and hydrological features into analogous richness measures. Diamicton was the most often encountered geofeature across the studied plots (see Figure 4 in Article I, Figure 2 in Article II, and Figure 2 in Article III). In turn, the most prevalent geomorphological geofeature throughout the study area was physical weathering, while the most frequent hydrological geofeature was the ephemeral channel (Articles I, II, & III).

Georichness, as the simplest quantitative measure of alpha geodiversity in this thesis, varied between 1 and 11(5 m radius), 1 and 14 (10 m radius), and 4 and 18 (25 m radius) in Article I and between 1 and 11 in Articles II–III (5 m radius used in both). In the example case in Article I, we explored the relationship of georichness from radii 5, 10, and 25 m and species richness (2 m × 2 m) to validate the most suitable radius for georichness to go with vegetation data plots. Species richness correlated positively with georichness across the scales, but the connection was strongest within the 5-metres scale (Figure 6) with a Spearman's correlation rank (R_s) of 0.32 with p-value of 0.004. This suggests that the 5-meters scale is adequate to match our vegetation plots.

In all articles georichness was measured using mean values that were calculated for each class. In Article I, we found out that the average georichness increased with the size of the plot. In Articles II and III georichness was explored within the classes (in Article II: isolated, low-lying mountain heaths, sporadic mountain heaths and tundra, and

Table 2. Summary of the main findings and contributions reflecting research questions. I–III referes to the original article number.

Question	I–III	Main findings	Contributions
Q1 How can fine-scale geodiversity be observed and quantified?	I	• Fine-scale geodiversity can be successfully observed in the field through predefined geofeatures. This information can be applied to quantify geodiversity, e.g., georichness.	• A widely applicable field method for observing and producing comprehensive information about fine-scale geodiversity.
	II	• Georichness can be used in species richness studies also in fine scales.	• The fine-scale geodiversity variable and the biodiversity variable should use the same measure to effectively use the former as the explanatory variable in species richness models.
	III	• In addition to georichness, alpha geodiversity can be estimated with accumulation curves, which proved to be suitable and informative way to estimate alpha geodiversity. • Information about fine-scale geofeatures can be used to calculate beta-geodiversity metrics (Jaccard's dissimilarity) and to investigate geocomposition (NMDS, PERMANOVA) effectively.	• Information on fine-scale geodiversity can be used to produce quantitative alpha- and beta-geodiversity metrics and to explore the geocomposition of the study sites, which is a major advancement in quantifying fine-scale geodiversity.
Q2 How does fine-scale geodiversity relate to vegetation patterns in boreal-Arctic heathlands and tundra?	I	• Georichness was positively correlated with vascular plant richness, especially with the shortest (5 m) radius and in sites dominated by deciduous shrubs.	• Even a simple measure of georichness shows a relatively strong connection between fine-scale geodiversity and vascular plant richness.
	II	• Georichness was positively related to species richness in all vegetation groups in continuous mountain tundra and lichen species richness in isolated, low-lying mountain tundra.	• Georichness can improve species richness models, but its effect on species richness can be context-dependent.
Q3 How does land use in ski resorts affect fine-scale geodiversity?	III	• The number of different geofeatures was highest in semi-disturbed sites and lowest in disturbed sites. • Land use altered geocomposition by eliminating some types of geofeatures and triggering new processes. • For soil variables, pH was observed to be higher in disturbed sites.	• Intermediate disturbance seems to favour the highest number of different geofeatures. • Ski resort–related land use changes the fine-scale occurrence of different geological, geomorphological and hydrological geofeatures. • Land use disturbance increases soil pH.
Q4 What information on fine scale geodiversity measurements can offer for conservation and land management?	I	• A simple method for practitioners interested in utilizing the information about fine-scale geodiversity.	• The fine-scale geodiversity method can be used to gather comprehensive information about geodiversity in a cost-efficient manner.
	II	• Georichness can be used to support species richness assessments.	• Fine-scale geodiversity can be implemented in biodiversity management and conservation.
	III	• Fine-scale geodiversity information can be used to assess the impact of land use on geodiversity.	• Fine-scale geodiversity should be implemented in nature monitoring and evaluations to support land use planning and conservation.

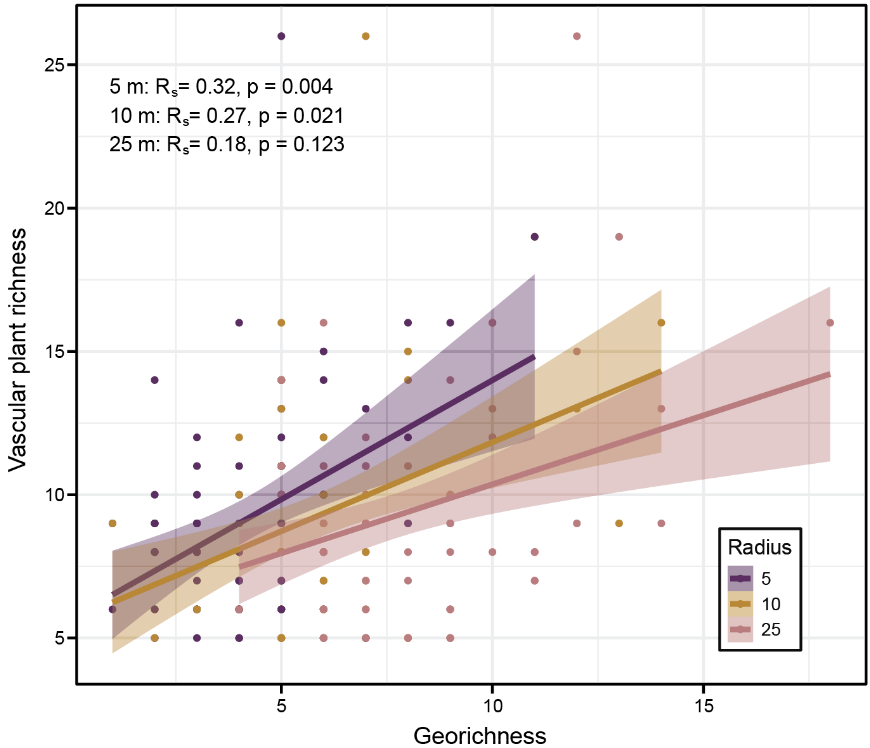

Figure 6. Relationship between species richness of vascular plants and georichness at 5, 10, and 25 m radii study plots (N = 76). R_s = Spearman's coefficients and p = statistical significance.

continuous mountain tundra; in Article III undisturbed, semi-disturbed, and disturbed). In Article III, alpha geodiversity was also explored with accumulation curves (Figure 8a), which showed an asymptotic curve for the whole study area, indicating an adequate number of geodiversity plots sampled to capture the geofeatures of the study area.

Beta geodiversity was successfully quantified in Article III. Unique observations of geofeatures provided an opportunity to include beta-diversity metrics into analyses (Jaccard's dissimilarity) and to examine the geocomposition (NMDS, PERMANOVA) of study plots.

8.2 Georichness is positively connected to species richness at a fine scale

This section provides results for the second research question of this thesis (**Q2**): How does fine-scale geodiversity relate to vegetation patterns in boreal-Arctic heathlands and tundra? Findings from Articles I and II are presented.

In correlation analyses of Article I, we found positive correlations between georichness and species richness in two habitat types: deciduous shrub and evergreen shrub-dominated sites (see Figure 5 in Article I). The correlation was statistically significant and positive (Spearman's Rs = 0.59, p = 0.004) only for the deciduous shrubs type. NMDS showed that peat-indicating geofeatures increased the species richness of vascular plants and bryophytes in isolated, low-lying mountain heaths and vascular plant richness in sporadic mountain tundra. In Article II, both univariate and multivariate GLMs (Figure 7; see also Figure 4 in Article II for univariate models) showed that georichness has a statistically significant ($p < 0.005$) positive relationship in all species groups (vascular plant richness, bryophyte richness, lichen richness, and total species richness) in continuous mountain tundra. In other regions, a statistically significant ($p < 0.005$) relationship was found in isolated mountain tundra between lichen richness and georichness. Thus, georichness performed well in GLM multivariate models, where other traditional environmental predictors were also considered (Figure 7).

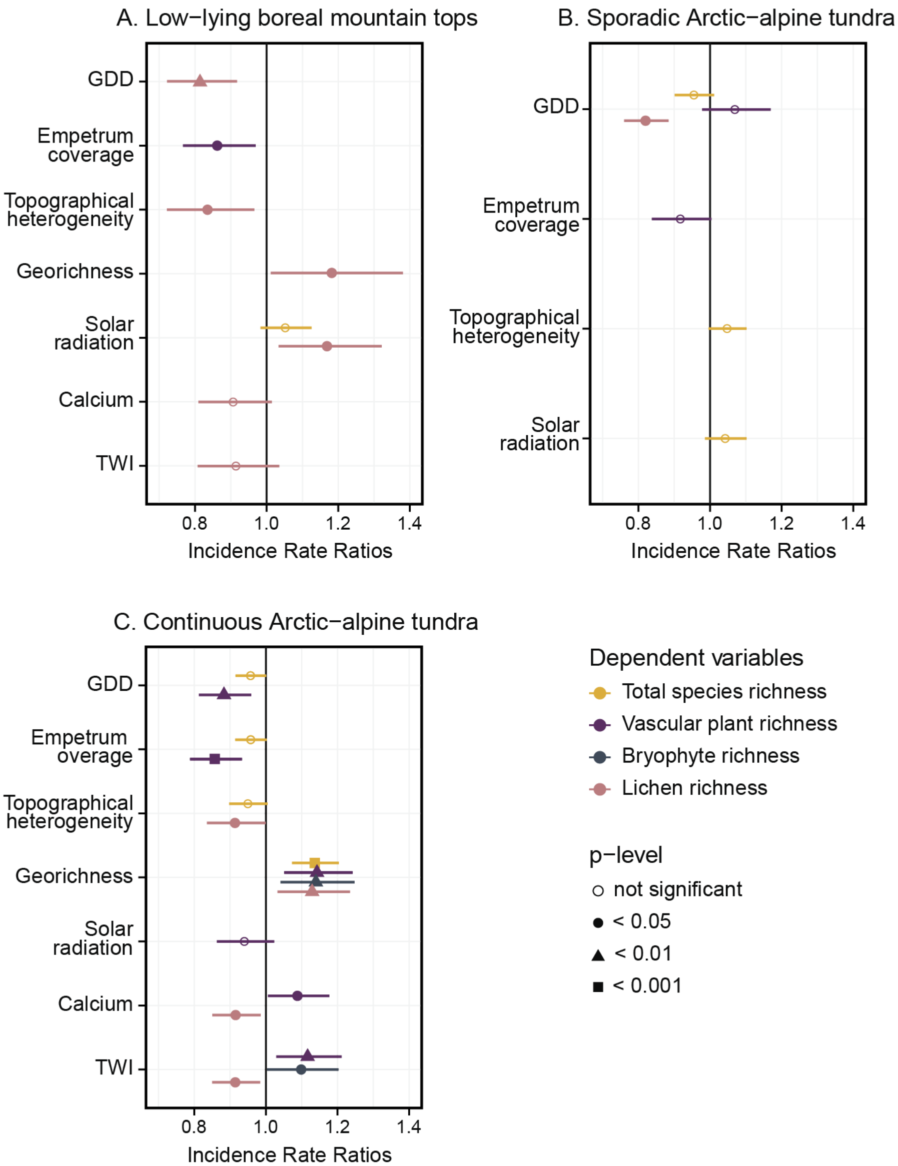

Figure 7. Forest plots illustrating environmental variables included in the optimal generalized linear models (GLMs) for total, vascular plant, bryophyte, and lichen richness in (A) isolated, low-lying mountain heaths, (B) sporadic mountain heaths and tundra, and (C) continuous mountain heaths and tundra. Estimates are incidence rate ratios with 95% confidence intervals. GDD = growing degree days. TWI = topographic wetness index.

Among the significant predictors in the multivariate GLMs, solar radiation showed a positive association with lichen richness, whereas GDD and topographical heterogeneity were negatively associated with lichen richness in isolated, low-lying boreal mountain-tops (Figure 7). In the same area, *Empetrum* coverage had a negative effect on vascular plant richness. In sporadic Arctic-alpine tundra, GDD was negatively associated with lichen richness. In continuous Arctic-alpine tundra, GDD and *Empetrum* coverage had negative effects on vascular plant richness, while calcium availability and TWI exerted positive effects. TWI also positively influenced bryophyte richness. In contrast, topographical heterogeneity, calcium, and TWI were negatively associated with lichen richness. When georichness was included in the multivariate models, its association with species richness was consistently positive across all species groups. In contrast, predictors such as topographical heterogeneity exhibited varying effects among habitat types, and calcium availability exhibited divergent effects depending on the species group considered.

8.3 Land use modifies fine-scale geodiversity

Results for the third question (**Q3**) are derived from Article III, where land use effect on fine-scale geodiversity was studied in three land use classes: undisturbed sites, semi-disturbed sites, and disturbed sites. I will first introduce land use effects on the studied alpha geodiversity variables and then continue with beta-geodiversity results. The average fine-scale georichness across the whole study area was 4.88 ± 0.15, and there were no statistically significant differences in means among different land use classes according to ANOVA. However, accumulation curves (Figure 8a) showed that semi-disturbed sites have the highest number of different geofeatures and disturbed sites the lowest. This indicates that in semi-disturbed sites the total diversity of geofeatures was highest. Asymptotic accumulation curves also show that the number of study sites is adequate to describe the geodiversity of this study area.

From a total of 12 soil variables, which were gathered from the study plots and studied in addition to georichness, only the mean pH showed a statistically significant difference between the disturbance classes. On average, the soil is acidic throughout the study area, but mean pH was significantly higher in disturbed sites compared to undisturbed and semi-disturbed sites. This was confirmed by Tukey's HSD test, where semi-disturbed and disturbed sites ($p = 0.001$) and undisturbed and disturbed sites ($p = 0.019$) differed statistically significantly.

The overall beta geodiversity, quantified with Jaccard's dissimilarity index, was consistently high across all disturbance classes (0.96 for all land use classes), turnover components varied between 0.94 and 0.95 and the nestedness component between 0.01 and 0.03. High turnover components indicate limited overlap in geocomposition among sites, whereby geofeatures absent from one site are replaced by distinct types in another. In NMDS ordination, standard deviation ellipses of different land use classes are partly overlapping (Figure 8b). However, results of PERMANOVA revealed statistically significant differences in geocomposition among disturbance classes ($R^2 = 0.025$, Pseudo-F = 3.2866, $p < 0.003$; for more detailed description, see Article III supplementary materials Table S1). The majority of fitted environmental vectors in the ordination plot were positively aligned with geofeatures indicative of moister soil conditions and higher organic matter content, such as fluvial features and peat-based features (Figure 8).

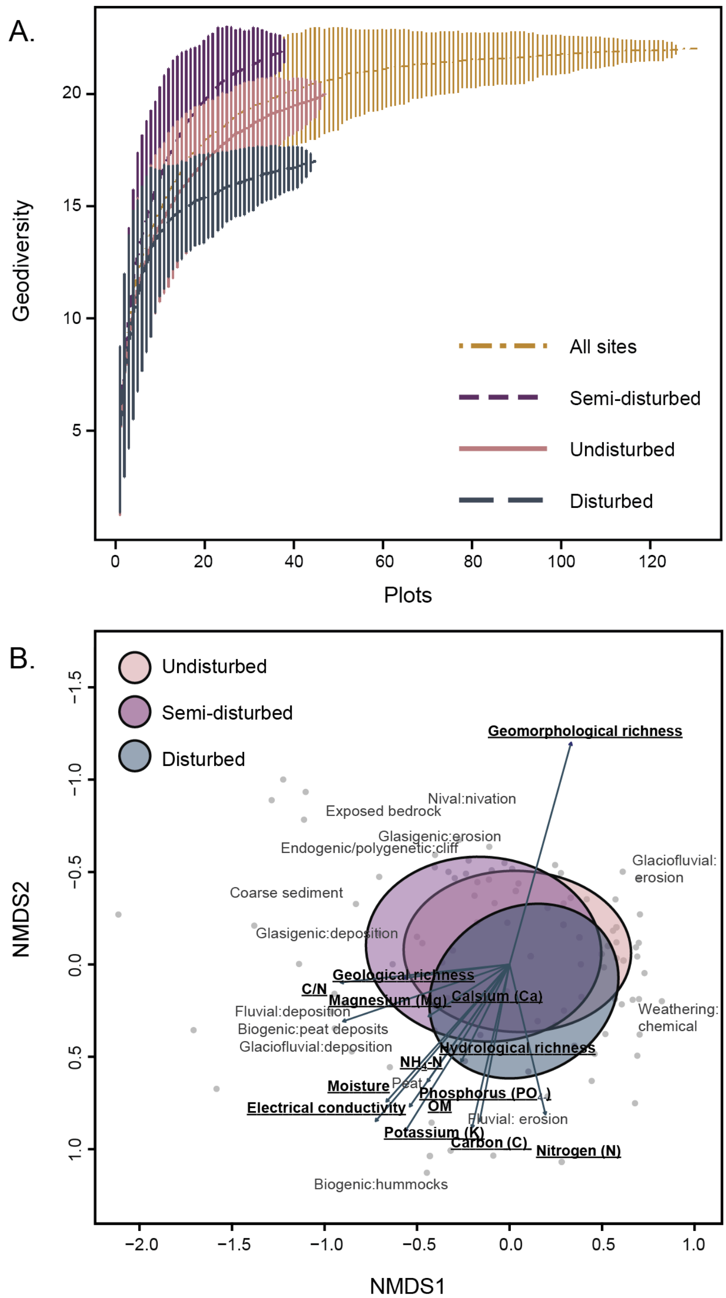

Figure 8. (A) Accumulation curves of geofeatures in all sites (yellow), undisturbed sites (light pink), semi-disturbed sites (violet), and disturbed sites (dark blue). (B) Panel shows geofeatures observed in the study plots in non-metric multidimensional scaling (NMDS) ordination. All geofeatures displayed in the figure belong to the 70 % most abundant and most fitting geofeatures. Different colours denote the level of disturbance: undisturbed sites (violet), semi-disturbed sites (light pink), and disturbed sites (dark blue), with 1 standard error ellipse drawn around the centroid of each level. Dark blue arrows display those variables that have a significant correlation ($p < 0.05$) with the ordination.

9 Discussion

This doctoral thesis is the first of its kind to investigate fine-scale geodiversity, from its mapping to applications in biodiversity and land use research. A key contribution of the thesis is in providing a fine-scale geodiversity framework from field observation to further geodiversity analysis (**Q1**), which can be used and developed in future studies and approaches. In addition to developing this framework, in this thesis I provide empirical evidence on timely questions related to the fine-scale connection between geodiversity and biodiversity in Arctic-alpine environments (**Q2**) and the vulnerability of geodiversity to land use (by using ski resorts as an example, **Q3**). Finally, the thesis considers the practical value of fine-scale geodiversity measurements for conservation and land management (**Q4**), where complementary strategies are needed to improve planning and decision-making.

9.1 Observing and quantifying fine-scale geodiversity

In this thesis, I offer a systematic methodology for observing fine-scale geodiversity in the field (Article I). The obtained data can be used in further quantitative analysis (Articles I–III; Q1). Previously, fine-scale geodiversity has been assessed, for example, in river habitats by observing streamflow diversity (Kärnä et al. 2018) and in semi-arid habitats through topographical variation (De Falco et al. 2021). Recently, fine-scale geodiversity method (Article I) has also been successfully applied in the data collection conducted in South Africa grasslands as a part of plant trait investigations (Halbritter et al. 2025), in middle boreal forests (Tukiainen et al. 2024), in northern boreal forests in Finland (Kotilainen 2024), and in an alpine system in central Norway (Reisæter-Thu 2021).

Our results and observations describe the rugged landscapes of oligotrophic boreal-Arctic heaths in a rather expected way. Observed geofeatures describe in detail what kind of geodiversity is present in the study area and more generally in oligotrophic boreal-Arctic heaths. Expectedly, the most common geofeatures were diamicton from geological, physical weathering from geomorphological and ephemeral stream from hydrological features.

Georichness as a variable has been used in geodiversity literature especially in landscape-scale studies (Toivanen et al. 2024; Tukiainen et al. 2016, 2024), and it is recognized as an essential geodiversity variable (Schrodt et al. 2024). The combined use of quantitative (how many) and qualitative (which geofeatures) geodiversity assessments is especially valuable when exploring how to identify microhabitats or refugia important for maintaining biodiversity during global change (Gonçalves et al. 2022). Articles I, II, and III show that georichness is informative and important in fine-scale geodiversity studies as well. Utilizing ecological concepts and methods, such as alpha- and beta diversity, and NMDS, accumulation curves and statistical analysis methods commonly used in ecology worked adequately with fine-scale geodiversity data that were collected by following the method in Article I. Results from applying the method are further discussed in the following sections. Future steps in observing fine-scale geodiversity in the field should aim for assessing not only presence-absence data but also the abundance of geofeatures, meaning for example relative estimates of the area geofeatures cover of the study plot. This continuum enables integration of fine-scale geodiversity data with corresponding ecological variables, advancing geodiversity–biodiversity research.

However, the field observation method is now developed in northern Arctic-alpine environments, and it should continue to be tested in other environments when studied in relation to biodiversity. As could be seen in Article II, the relationships between georichness and species richness variables were not statistically significant on isolated mountain-tops or sporadic mountain tundra, excluding lichen richness at isolated mountain-tops. This result suggests that the relationship is context-dependent. In fine-scale studies, the context-dependency of environmental variables, such as geodiversity variables, must be considered when making biodiversity models in other environments. In addition, different geofeatures can be important for different species or species groups. Therefore, future studies should consider if ecological weighting of geofeatures would be beneficial. It would also be beneficial to develop the field method into more detailed taxonomical depth, following Hjort et al. (2024) primarily for scientific purposes. This would deepen understanding of fine-scale geodiversity patterns to a very detailed level.

Observation, and therefore quantification of geofeatures is directly dependent on classification, but classification of geodiversity may be problematic (see Ibáñez & Brevik 2022). Counting elements of geodiversity can be more difficult than counting biological species as geofeatures exist as continua (Gray 2022). It could be argued that this claim is too simplified, as classification of species in the field of biology is not easy or flawless and has developed over time to post-Linnaean practices. It is nevertheless important to ask whether classification of geodiversity is hard because it exists as continua or because we do not have as long a tradition of classifying geodiversity at the "species level" as in biology. These problematics of classifying geodiversity should be considered when developing methods to observe and measure fine-scale geodiversity. Based on my experiences, some practical problems do not arise until one is in the field: not only defining the class borders in continuous phenomena, such as poorly sorted sand and sandy diamicton, but also the fact that much of the geodiversity is hidden under vegetation or would require destructive practices to classify features in detail. In this sense, Article I's method, while robust, captures the variability of geofeatures efficiently while being as non-invasive to nature as possible.

9.2 Fine-scale geodiversity's relation to Boreal-Arctic vegetation

Fine-scale approaches are essential for understanding the intricate relationships between geodiversity and biodiversity patterns. While coarse-scale assessments provide broad insights and serve their own purpose (Toivanen et al. 2019, 2024; Zarnetske et al. 2019), they often mask localized variations that drive species distributions and ecological processes. Fine-scale analyses enable researchers to capture microhabitat features, such as soil texture, microtopographic complexity, and substrate diversity, that strongly influence species richness and community composition. This thesis shows empirically that fine-scale geodiversity provides information about critical abiotic heterogeneity that supports ecological niches and enhances biodiversity in boreal-Arctic tundra environments, which have climatically and topographically complex landscapes (Articles I & II; Q2). The inclusion of information on geodiversity at different scales has proven useful in species richness modelling in the other studies conducted in northern environments as well (Bailey et al. 2017; Hjort et al. 2012; Tukiainen et al. 2017a).

The positive correlation that I found between species richness and georichness in Article I suggests that geodiversity data collection should be planned carefully with the planning of the size of the vegetation plot (Figure 6). Geodiversity data should be collected from the imminent surroundings of the vegetation plot, covering a slightly larger area. In a dry environment like oligotrophic mountain heaths and tundra, this ratio (5 m radius georichness for 2 m × 2 m vegetation plot) was observed as the most suitable, but this should be assessed for different habitats and study settings. There is a great number of explanatory variables used in ecology, which interact with each other, to predicate species richness. The correlation between georichness and species richness on the 5 m scale is relatively good ($R_s = 0.32$ and $p < 0.005$; Article I) even though only presence-absence data were used. This is promising for later studies on geodiversity–biodiversity relationships. In some environments enlarging the mapping area could be recommended because geofeatures affect adjacent conditions, such as soil moisture and microclimate.

Fine-scale geodiversity is a significant predictor of vascular plant, bryophyte, and lichen richness in Boreal-Arctic heath ecosystems, when oligotrophic tundra areas are large and continuous (Article II). The continuous mountain tundra hosts the largest species pool within our study area. When the local species pool is small, increased geodiversity may not translate into higher species richness due to limited dispersal. Within this thesis, this might be the case in isolated, low-lying mountain heaths and sporadic mountain heaths and tundra, where the relationships between georichness and species richness were not as evident as in continuous mountain tundra. Georichness also predicts lichen species richness in isolated, low-lying mountain-tops. In other regions and depending on the species group, the strength and direction of this relationship vary. For example, the extensive increase in shrub abundance in isolated boreal mountain heaths (Maliniemi et al. 2018; Maliniemi & Virtanen 2021; Maliniemi et al 2025) may complicate the observation of the potential positive link with geodiversity and biodiversity, as shrubs occupy niche space and have a negative effect on species richness. Lichens may persist within geodiverse areas because they favour dry and relatively barren conditions (Jonasson 1981) typically associated with features such as glaciogenic erosion, aeolian erosion, and physical weathering.

Multivariate GLM models showed that fine-scale geodiversity can have additional importance for species richness models beyond the well-known environmental variables that are conventionally used to explain boreal-Arctic vegetation patterns (Figure 7). In the models from continuous Arctic-alpine tundra, georichness was the only environmental variable that had a statistically significant ($p < 0.05$) effect on the richness of all species groups, including variables that are generally known to be important for species richness in northern areas, such as GDD and calcium concentration. This highlights the importance of site-specific geological, geomorphological and hydrological variation for plant biodiversity and is in line with the CNS strategy, where geodiversity is seen as the diverse stage for different species to coexist (Beier et al. 2015).

Georichness apparently catches abiotic variation not reached by other environmental variables used in Article II. With used study set-up it is not possible to determine exact processes and mechanisms behind the positive effect of geodiversity to species richness, though they are presumably linked to variation, for example, in microclimatic conditions and in the soil properties. The negative effect of *Empetrum* cover to vascular plants, positive effect of TWI to vascular plants and bryophytes and on the contrary on lichen richness, and the effect of the amount of calcium to alkalinity were in line with previous literature (Bråthen et al. 2010; Kemppinen et al. 2019; le Roux et al. 2014; van der Welle et al. 2003). In addition, the negative effect of GDD to lichen richness was to be expected (Niittynen et al. 2020). In the future, it could be worthwhile to explore the relevance of geodiversity compared to other environmental variables. This could be done, for example, with structural equation models such as path analysis to deepen the understanding of georichness's direct and indirect effects on species richness. In addition, geocomposition analysis (NMDS) showed that the presence of organic material (in this study area that is peat) seemed to increase vascular plant and bryophyte richness in isolated, low-lying mountain heaths and vascular plant richness in sporadic mountain heaths and tundra. Continuous mountain tundra differs from the other two regions, as there the presence of ephemeral channels, exposed bedrock and cliffs were related to total and bryophyte richness. It is explained by the peatland-specific vegetation that would not otherwise occur in mountain heaths and tundra of the study area. In addition, Article I revealed the difference between two habitat types, evergreen shrubs dominated and deciduous shrubs dominated habitats, where statistically significant relationship occurred only in deciduous shrubs dominated habitats. Plots dominated by deciduous shrubs also had larger species pool than evergreen shrubs dominated plots, and geodiversity is offering the niches for different species to grow (See Article I Figure 5b). Both articles suggest soil moisture as the central factor for species richness. In Arctic-alpine environments, water and soil moisture are crucial for species richness (Kemppinen et al. 2019). Seasonal streams, cliffs and exposed bedrock catch runoff, and provide microhabitats with higher soil moisture. In addition, the dominant species of evergreen shrubs dominated plots, *Empetrum nigrum* ssp. *hermaphroditum,* has shown to have negative impact on vascular plant richness in the tundra (Bråthen & Ravolainen 2015). Importantly, its abundance has strongly increased in northern European tundra over the recent decades (Maliniemi et al. 2025) and this may have a strong control over current species compositions.

Because this study is among the first ones to test geodiversity–biodiversity relationship at the fine scale, the underlying mechanisms are tentative. Varying relations between species richness and georichness imply their connection to being context-dependent. For instance, the relationship may vary depending on species group, the location of the study plots or that the importance of other environmental variables overrides the effect of fine-scale geodiversity in explaining species richness, as suggested also by Toivanen et al. (2019). For example, it remains uncertain how exactly different geofeatures translate into niche availability, microclimate variation, or soil heterogeneity that favours species richness. Thus, integrating quantitative and qualitative fine-scale geodiversity metrics into ecological frameworks could improve the detection and interpretation of biodiversity patterns in heterogeneous environments (Gonçalves et al. 2022). In addition, fine-scale investigations can shed light on large-scale geodiversity–biodiversity relationships by exploring deeper into the processes and mechanisms that underlies observed phenomena (Stavi et al. 2019; Tukiainen et al. 2023). This is especially important in Arctic-alpine environments to which global change is prominently affecting (IPBES 2019; IPCC 2021). For example, recent study shows vegetation in Boreal-Arctic heathlands of northern Fennoscandia are facing homogenization as evergreen dwarf shrubs, particularly *Empetrum nigrum*, are colonizing other vegetation types (see e.g. Maliniemi et al. 2025). In the future, fine-scale geodiversity studies should study if there are key geofeatures that are specifically important for, for example, endangered species. Species are recorded to have different responses to geodiversity variables in species distribution models (Gerstner et al. 2024).

9.3 Human land use changes fine-scale geodiversity

Land use, such as ski resort development, can significantly alter fine-scale geodiversity, with potentially cascading effects on biodiversity and ecosystem functioning (Gray 2013). The results of this thesis provide information on how fine-scale geodiversity changes with the disturbance of human activities (Article III; Q3). Geodiversity explorations produce invaluable information on nature that can be used to guide decision-makers for a sustainable future (Gordon et al. 2022; Ibáñez et al. 2019; Tukiainen et al. 2017). Article III evaluated alpha geodiversity using two metrics in all three disturbance classes (undisturbed, semi-disturbed, and disturbed) with ski tourism–related land use. Average georichness did not show statistically significant differences between the classes, but the values were slightly higher in semi-disturbed study plots, than in disturbed or undisturbed plots. Respectively, when accumulation curves are observed, georichness was highest in the semi-disturbed sites, and disturbed sites had the lowest (Figure 8a). This result suggests that the intermediate disturbance hypothesis (IDH) might be applicable to geodiversity as in ecology, where the concept originates from (Connell 1978). The IDH describes species colonization and competition dynamics, where species coexist especially during intermediate disturbance (Moi et al. 2020). In the context of geodiversity, these results suggest that sensitive geofeatures, such as glasigenic erosion and peat deposits still exist, but alongside them, disturbance triggers erosional processes that create new geofeatures.

Increasing land use generally changes soil properties (Batlle-Aguilar et al. 2010). The results of this thesis showed that disturbance raises pH on the soils, which has also been reported in literature on the Alps (Barni et al. 2007; Casagrande-Bacchiocchi et al. 2019; Roux-Fouillet et al. 2011) and on built environments in tundra landscapes (Auerbach et al. 1997). Fennoscandian Arctic-alpine environments typically have acidic soils (Darmody et al. 2000). An increase in pH may be beneficial for plant species, especially for more alkaline soils favouring vascular plants, to colonize disturbed areas (Gough et al. 2000). Other soil variables showed indifferent reactions to land use changes, which may be related to slow soil processes typical of high latitudes, but also, disturbance may have the same effect of naturally occurring soil-mixing processes. The NMDS results showed that geofeatures related to moisture and organic material are linked to soil variables. Soil variables were considered separately since they describe only chosen parts of the particle-level aspect of soil geodiversity, not its full extent, and the hierarchical level differed from other geodiversity elements (Hjort et al. 2024; Serrano & Ruiz-Flaño 2007). Results imply that soil samples are not necessarily needed when assessing the land use impact on nature; presence-absence fine-scale geodiversity data may suffice.

Generally, it is thought that geodiversity declines with increasing land use (Gray 2013). The results of this thesis show that the total amount of beta geodiversity was similar in all disturbance classes, whereas palpable changes occurred in the geocomposition of the geofeatures on studied plots (Figure 8). This means land use also changes what kinds of geofeatures are present. Some of the geofeatures were observed across the disturbance classes, such as diamicton, stones and blocks, and physical weathering. It is evident that the destroyed or deteriorated geofeatures were those that had developed through history and were not active geomorphological processes, such as geofeatures that originate from the last ice age (e.g. glaciogenic deposition, glaciofluvial erosion and deposition features). These might get destroyed during construction of and levelling the ground for ski pistes and other infrastructure (Freppaz et al. 2013). However, tourism-related land use activates processes that might not be present in the plot locations naturally. Results showed increases in erosional landforms, such as chemical weathering, cryogenic geofeatures, and fluvial erosion. Clearing and machine-grading of ski pistes prompts soil erosion (Mosimann 1985), and in using artificial snow, the larger amount of meltwaters induces it further (Isselin-Nondedeu & Bédécarrats 2007). Soil erosion is also induced by hiking trails, although the impact is on narrow areas along the paths (Tolvanen & Kangas 2016). On ski pistes, the insulation capacity of snow is decreased due to its compactness, which causes ground freezing (Rixen et al. 2004); this could be observed in the results that showed relatively higher numbers of cryogenic geofeatures such as cryoturbation. Furthermore, some geofeatures are avoided during the construction of ski slopes and tourism infrastructure, such as steep cliffs, which were not present at disturbed plots or were just levelled off.

This opens discussions about what is counted as geodiversity and how human actions are seen as a part of nature. In the geodiversity definition of Gray (2013), only the natural range of geodiversity is geodiversity. All the processes here occur naturally on Boreal-Arctic heaths, but it seems that some geofeatures are induced by land use. We need discussion and research studying man-made and urban geodiversity (Del Monte et al. 2016; Wolniewicz 2022) as land use takes more space in our environments.

9.4 Fine-scale geodiversity and practical implications

Decision making, sustainable development and resource use planning need information on geodiversity (Brilha et al. 2018; Schrodt et al. 2019). Assessing fine-scale geodiversity is an essential step in achieving knowledge-based conservation and optimal land management decisions. Because geodiversity is considered more stable over time, when compared to changes in biodiversity, it might serve as a planning tool under environmental change (Lawler et al. 2015). On the other hand, the results from Article III show that human actions can also have an impact on geodiversity.

This field observation method will further enable consistent integration of fine-scale geodiversity into biodiversity research, and further, into conservation planning (Q4). With its outcome of georichness variables and qualitative information about individual geofeatures, it is feasible to implement ecological concepts and methods into geodiversity research (Tukiainen et al. 2022a). Furthermore, mapping fine-scale geodiversity through geofeatures is relatively cost-effective and suitable for observers without extensive knowledge of geology or geomorphology. For example, knowledge on individual geofeatures in sub-plot and plot scales can be used to assess the relationship with abiotic nature and individual species as well as species richness. At habitat and landscape levels, georichness and geofeatures can provide insight into species richness patterns and ecosystem functions. Finally, on a regional scale, information on fine-scale geodiversity can be used to reveal human impacts on geodiversity and nature and thus guide land management decisions. Therefore, I recommend the inclusion of field-based fine-scale geodiversity data for exploring the geodiversity of Arctic-alpine environments. To date, remotely sensed (RS) data are not as accurate and to develop comprehensive RS fine-scale geodiversity datasets, there will be still need for field data for validating RS data.

We already know relatively well how different unique environmental variables (such as pH, soil moisture or human- and animal disturbances) affect vegetation and species patterns. However, geodiversity holistically, as an umbrella concept, ties these phenomena together in tangible and more applicable way, as field surveyors rarely have the time and resources needed to measure and sample specific variables, e.g. via soil sampling. Incorporating fine-scale geodiversity metrics into conservation planning and land management would support more accurate estimations of biodiversity patterns and more effective mitigation of anthropogenic impacts (Gerstner et al. 2024; Tukiainen et al. 2017). For example, fine-scale geodiversity could be a relatively simple and stable proxy or predictor for species richness in biodiversity assessments that support conservation planning. This would be especially useful in places where species surveys are difficult or resource-intensive.

Further, considering fine-scale geodiversity when planning new tourist attractions and aiming for sustainable tourism is crucial, as land use can affect geocomposition permanently (Article III). A set of management measures needs to be considered before tourism planning. Tourism causes damage to geodiversity in sensitive areas, which raises the need to establish management measures before tourism activities and new land use strategies are planned and put into action (Kubalikova et al. 2024). This would reveal temporal aspects of geodiversity's relationship with land use disturbances. Sustainable tourism planning and regulation call for smart and responsible measures that take into account geoconservation jointly with biodiversity conservation (see Tukiainen & Bailey 2022). Despite the growing recognition of geodiversity and geoconservation, nature conservation efforts are currently targeted at protecting biodiversity (Brilha & Reynard 2018; Schrodt et al. 2019). It is imperative that geodiversity be factored alongside biodiversity for conservation research but also in conservation practices (Chakraborty 2020).

Geodiversity has intrinsic value besides its relationship with biodiversity or via the geosystem services it provides for humankind (Brilha et al. 2018; Gordon et al. 2012; Gray 2013, 2019). Based on the results of this thesis, fine-scale geodiversity should be recognized as a vulnerable component of natural systems requiring active monitoring and management in the face of anthropogenic pressures and climate change. Due to global change, we are facing the loss of landforms and processes of the Arctic environments (Karjalainen et al. 2020), such as palsas (Leppiniemi et al. 2023). Land use changes are adding to this loss but are easier to avoid with careful planning practices. These require versatile information on nature and its state. This thesis gives practical tools for gathering this information, by demonstrating the use of a fine-scale geodiversity methodology in the field, as well as in analytical approaches.

10 Conclusions

This thesis improves our understanding of fine-scale geodiversity. In it, I provide an observation method for fine-scale geodiversity research (Article I) and demonstrate how it can be quantified and applied in research (Articles I–III). The method is based on observing geofeatures in the field, and the data conceived with it can be quantified by using concepts, methods and analyses derived from the field of ecology, such as alpha and beta metrics, accumulation curves, NMDS, and Jaccard's dissimilarity. These findings deepen our knowledge of geodiversity–biodiversity relationships in Arctic-alpine environments by showing geodiversity's positive relationship with species richness of vascular plants, bryophytes, and lichens, but also revealing its context-dependency (Articles I & II). In addition, this thesis reveals that ski tourism–related land use lowers the number of different geofeatures encountered, raises soil pH, and affects the geocomposition of the sites (Article III). These contributions create the foundation for future academic investigations from observing, to better understanding of fine-scale geodiversity and biodiversity patterns, and the vulnerability of abiotic environment to global change.

Knowledge on fine-scale geodiversity is crucial for practitioners because nature conservation usually happens locally, and therefore it is necessary to know how geodiversity varies in fine scales, how it is affected by human land use, and how it is connected with biodiversity, as geodiversity is a crucial part of nature's diversity. The approaches I have developed in this dissertation can be applied to meet both scientific and societal needs as a tool in land use and conservation planning. As my final claim, fine-scale geodiversity should be quantified in a systematic manner in order to achieve greater understanding of our nature – but also for more sustainable land management actions.

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Appendix 1

Printable field form, that was used on the field to gather fine-scale geodiversity data.

	Date:			Photo ID
Coordinates:	Observer:			
	5 m	10 m	25 m	
GEOLOGY				Notes
Exposed bedrock				
Diamicton				
Stones/blocks				
Coarse sediment (sand and gravel)				
Fine sediment (silt)				
Organic material				
GEOLOGY SUM				
GEOMORPHOLOGY				
Endogenic				
Cliff				
Fracture				
Glacigenic				
Erosion				
Deposition				
Glaciofluvial				
Erosion				
Deposition				
Aeolian				
Erosion				
Deposition				
Fluvial				
Erosion				
Deposition				
Littoral				
Erosion				
Deposition				
Biogenic				
Peat deposits				
Hummocks				
Mass movements				
Rapid				
Slow				

Cryogenic				
Cryoturbation				
Ground ice				
Nival				
Nivation features				
Snow avalanche or slush flow				
Weathering				
Physical				
Chemical				
GEOMORPHOLOGY SUM				
HYDROLOGY				
River/stream/rivulet				
Ephemeral channel				
Lake/pond/pool				
Ephemeral pond/pool				
Wetland				
Spring				
HYDROLOGY SUM				